THE UNIVERSITY OF ALBERTA

GEOLOGY OF THE HEART PEAKS VOLCANIC CENTRE NORTHWESTERN BRITISH COLUMBIA

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE

STUDIES AND RESEARCH IN PARTIAL

FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

SPRING, 1980

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Geology of the Heart Peaks Volcanic Centre, Northwestern British Columbia submitted by John Joseph Casey in partial fulfilment of the requirements for the degree of Master of Science.

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Date ...December 20, 1978.....

ABSTRACT

The Heart Peaks volcanics of northwestern British Columbia represent one of a series of late Cenozoic eruptive centres which form shields of alkali basalt and related volcanic rocks. The Level Mountain and Mt. Edziza Ranges are typical examples of this style of volcanism. The Heart Peaks plateau is a series of flat-lying, fine-grained and porphyritic flows and related pyroclastics belonging to the Level Mountain Group. Associated with the plateau lavas are rhyolite and trachyte domes of the Heart Peaks Formation. The acid rocks appear to be closely related to the plateau series, having been erupted contemporaneously but likely from different vents than the basic rocks.

Compositions in the Level Mountain Group range from ankaramite to andesite and trachyte. Major and trace element variation in Level Mountain Group rocks give trends indicative of a fractional crystallization sequence. Basaltic rocks are transitional to mildly alkaline. Alkali basalt and hawaiite are the most voluminous compositions. Basic rocks contain abundant cognate inclusions containing olivine, clinopyroxene, kaersutite, titanomagnetite, plagioclase and alkali-feldspar which is indicative of the mineralogy of the fine-grained eruptives.

Strontium and oxygen isotope compositions support a mantle origin for alkali basalt and high abundances of large-ion lithophile

elements are compatible with models where small degrees of partial melting of peridotite give rise to alkali basalt.

The rocks of the Heart Peaks Formation differ from acid rocks of other northern B.C. centres in their lack of peralkaline compositions. There are no alkali-rich ferromagnesian minerals which are typically found in acid rocks associated with the Level Mountain and Mt. Edziza Ranges. The close association in space and time of acid rocks to the basic rocks of the Level Mountain Group suggests a mutual relationship, but the lack of compositions in the intermediate range and the highly altered nature of the acid rocks makes this link obscure.

The importance of alkali basalt as a significant regional magma type is supported by data from Heart Peaks. Evidence from the Heart Peaks area supports Souther's (1970, 1977a) model for the tectonic regime of late Cenozoic volcanism in the Stikine belt of northern British Columbia, where alkali basalt magma is generated in a tensional tectonic environment.

ACKNOWLEDGEMENTS

I am grateful to Dr. C. M. Scarfe for supervision and to Drs. H. Baadsgaard, R. St. J. Lambert, K. Muehlenbachs, D. G. W. Smith and J. G. Souther (G.S.C.) for advice at various stages of the project.

Discussion, criticism and technical assistance were provided by J. Andersen, T. Dunn, T. S. Hamilton, S. Launspach, A. Stelmach and D. A. Tomlinson. Analyses were performed by Dr. K. Muehlenbachs and Dr. K. Hattori (oxygen isotopes), Dr. J. G. Holland (XRF at Durham University) and T. S. Hamilton (strontium isotopes).

The Department of Geology and the Boreal Institute for Northern Studies, University of Alberta are thanked for financial support. Additional funding was provided from EMR Research Agreement 2239-4-51/77 and NRC Grant A839A awarded to Dr. Scarfe.

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CHAPTER I

INTRODUCTION

This study of the volcanic rocks of the Heart Peaks plateau of northwestern British Columbia was begun in the fall of 1976 as part of a program to investigate late Cenozoic volcanism in the western Canadian Cordillera. Investigation of the geology and petrology of the Heart Peaks and Level Mountain volcanic centres was suggested by J. G. Souther of the Geological Survey of Canada, following studies of the Mount Edziza centre (Souther, 1970; Souther and Symons, 1974). The location of the study area is shown in Figure 1. Dr. C. M. Scarfe of the University of Alberta has initiated the Heart Peaks project as part of a continuing effort to characterize this episode of volcanism in northern British Columbia.

The broad objectives of the project are twofold:

i) to study the petrology of the Heart Peaks volcanic centre;

ii) to relate the volcanism to large scale tectonism in northern B.C.

Previous research in this area has emphasized the relationship between recent crustal movement in the northern Cordillera and associated volcanic belts (Souther 1970, 1971, 1977; Gabrielse and Wheeler, 1961). Information from the Heart Peaks centre is needed to complement data from other such centres in this region before a consistent model can be proposed to interpret the local tectonic regime. Previous

work in the Heart Peaks area has not involved any detailed petrological discussion. Preliminary petrographical observations were begun in the fall of 1976 and a detailed mapping project was begun in the summer of 1977 with the following objectives:

i) to delineate the areal extent of the two compositionally distinct rock units previously described in the area (Souther 1971);

ii) to describe the stratigraphic sequence of the volcanic units;

iii) to interpret the time-stratigraphic relationship between the map units;

iv) to observe physical volcanological aspects of the rocks and determine how these relate to their genesis.

In the discussion of the petrogenesis of the Heart Peaks volcanics a comparative approach may be appropriate, utilizing well known magma associations and tectonic regimes.

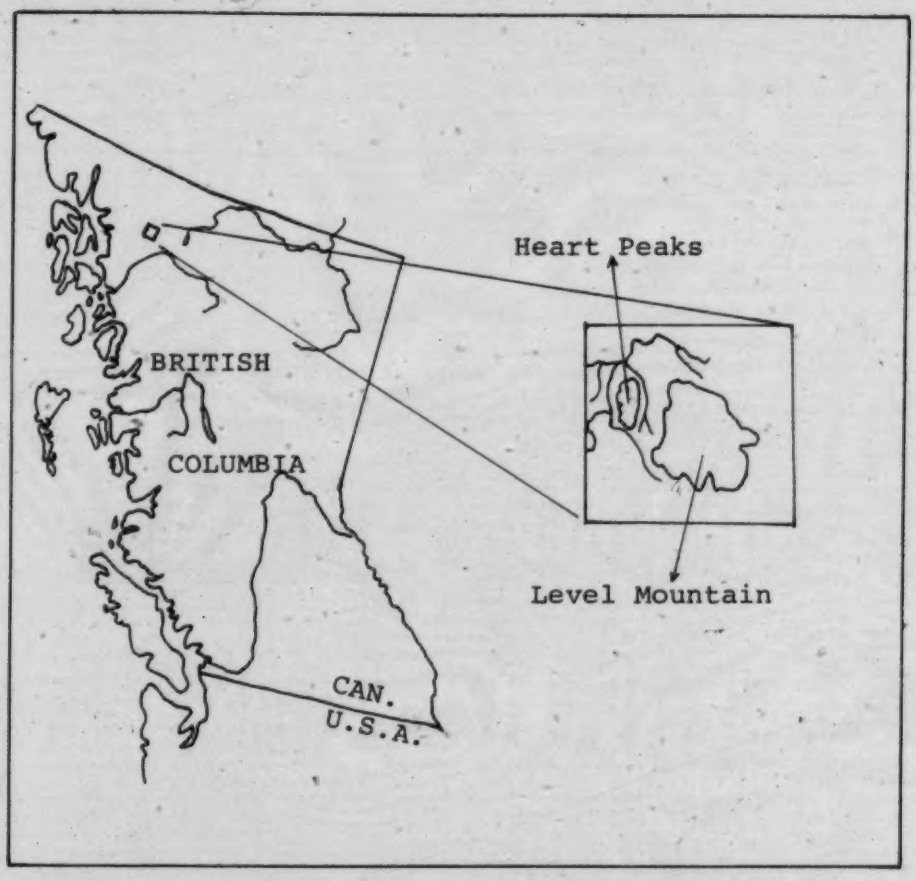


Fig.1. Location map,Heart Peaks area,northwestern British Columbia.

Foreground: Flat-lying flows of the Level Mountain Group

Centre: Rhyolite domes of the Heart Peaks Formation in vertical contact with LMG flows.

Background: View west across the Sheslay Valley and the Coast Mountain Range.

PLATE 1.

CHAPTER II

PREVIOUS WORK

Early reconnaissance expeditions through the Heart Peaks area were conducted in the 1920's in the hope of finding mineral deposits similar to the lead-zinc showings near Atlin to the north, and the placer gold occurrences near Dease Lake, to the east. W. E. Cockfield (1925) described the topography and general geology of the area and produced a map including the Cenozoic volcanics of Heart Peaks. He provided some petrographic observations on the lavas and noted that the acidic rocks appeared to be younger than the basic rocks. He suggested that the volcanics were late Tertiary and Quaternary in age. Since much of the area was underlain by these unmineralized, flat-lying volcanics, the economic potential of the area was considered poor and the Heart Peaks area has seen little exploration activity until recent years.

Mapping by Gabrielse and Souther (1962), and Souther (1971) defined the principal rock units present in the Heart Peaks plateau. The plateau is located partly on the Dease Lake sheet (Gabrielse and Souther 1962) and the Tulsequah sheet (Souther 1971). The work of Souther (1970) and Monger, et al. (1972) emphasized the role that Cenozoic volcanics play throughout the intermontane belt in understanding the tectonic evolution of northern British Columbia. From Eocene to Miocene times a fundamental change occurred from

calc-alkaline volcanism to activity of an alkaline to peralkaline nature. This change reflected changing tectonic relationships in the Canadian Cordillera. Early Cenozoic volcanism was calc-alkalic in character and this has been interpreted by Souther (1970) to indicate active subduction of oceanic crust beneath the western Cordillera. When the relative movement between the Pacific and North American plates changed from underthrusting to simple shear in Late Tertiary and Quaternary times, a corresponding change of eruptive style occurred, from explosive eruption of calc-alkaline lava to quiet eruption of alkali-olivine basalt. This late Cenozoic volcanism in northern British Columbia can be contrasted with the calc-alkalic volcanism of the Cascades of northwestern U. S. A. where the Pacific plate is being actively underthrust beneath the North American plate (Souther 1970).

Souther and Symons (1974) described the stratigraphy and paleomagnetism of the Mount Edziza complex, located 100 miles south of Heart Peaks, which represents the largest of the late Tertiary and Quaternary composite volcanoes in northern British Columbia. Paleomagnetic studies are used to correlate the volcanic succession and have illustrated the periodic nature of volcanic activity at Edziza. Edziza and the Level Mountain centre are important to the present study as they are the only local centres to which the Heart Peaks rocks may be directly compared. Edziza offers a complete stratigraphic section of volcanic activity from 6 m. y. b. p. through to very recent times. The sequence includes several episodes of uniform alkali olivine basalt

flows which are the predominant lava type in the pile. Alternating with the alkali basalts in each sequence are alkaline and peralkaline salic rocks.

Bevier (1978) has described alkaline and peralkaline volcanism in the Rainbow Range of west-central British Columbia and interprets the sequence as representative of a classical differentiation suite from a basaltic parent.

Figure 2 shows the distribution of Late Tertiary and Quaternary volcanics in British Columbia and Yukon, together with the regional fault patterns. There is a close relationship between the Edziza Range and north-south trending normal faults along which movement has occurred during the volcanism. North-south tensional faults associated with the Edziza pile offer a possible structural control for rising basaltic magma. The basaltic magmas were generated in four pulses of activity at 6.0 m.y., 5.0 m.y., 1.0 m.y., and 0.5 m.y. b.p.

The volcanics of the Level Mountain Range, a large shield plateau 16 km to the east of Heart Peaks are presently being studied (Hamilton and Scarfe, 1977; Hamilton, Baadsgaard and Scarfe, 1978). Though subordinate in volume, peralkaline salic rocks are important as flows in the central region. The Level Mountain Group basic rocks belong to the alkali basalt series but the origin of the associated peralkaline rocks is a matter for debate. Current investigators appeal to two mechanisms for the origin of the peralkaline salic rocks at Edziza and Level Mountain:

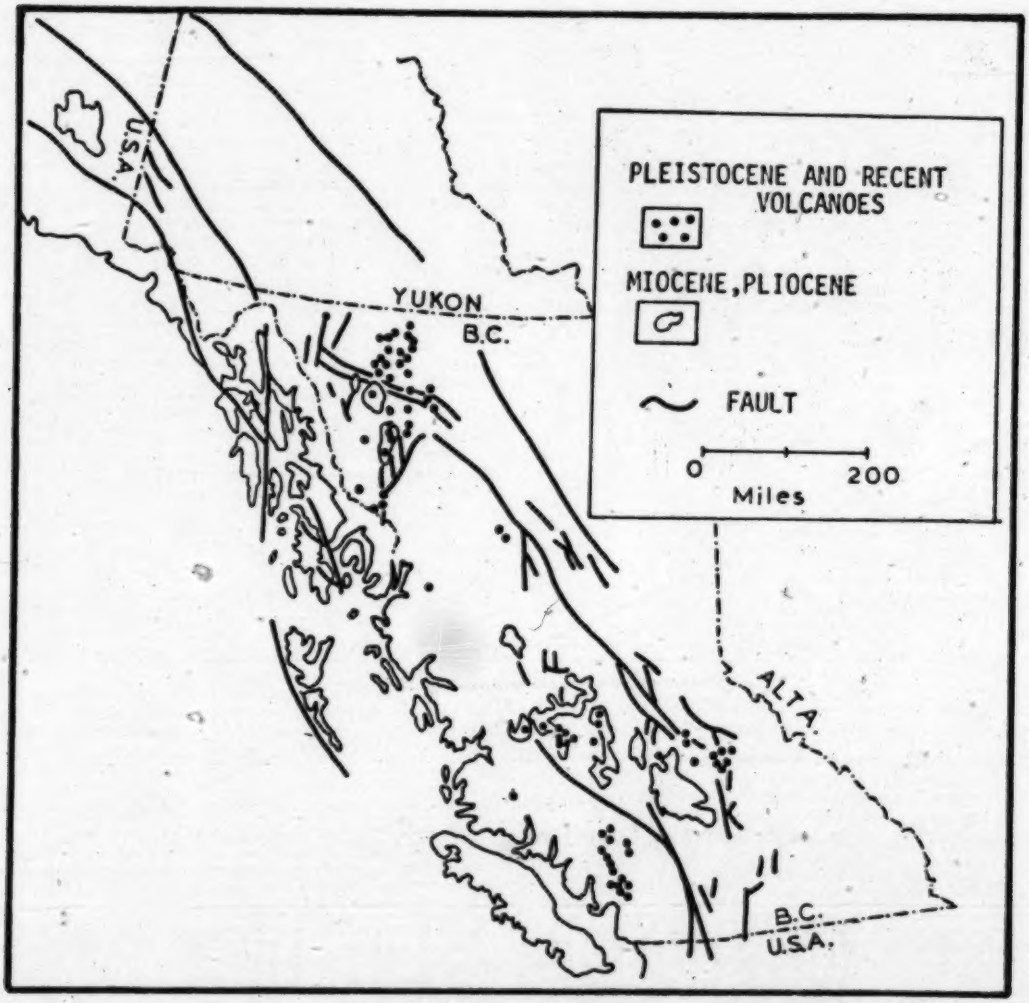


Fig. 2. Distribution of late Tertiary and Quaternary volcanic rocks of British Columbia and Yukon Territory. (after Souther, 1970)

a) by classic differentiation from a basaltic parent (Souther 1974; Bevier 1978).

b) as a primary magma type (Hamilton, pers. comm.).

The volumetric predominance of alkali basalt at Edziza and Level Mountain argues that it is a characteristic primary magma type.

Souther (1977) has reviewed volcanism and tectonic associations in northern British Columbia within a wide regional framework which includes the Wrangell Belt of southern Alaska and Yukon, and the Garibaldi and Anahim belts of southern British Columbia. The Level Mountain, Edziza and Heart Peaks centres are grouped into the Stikine belt. The Wrangell rocks appear to be analogous with those of the Garibaldi and High Cascades. The Wrangell and Cascade volcanics display calc-alkaline chemical trends typical of environments where subduction is occurring at continental margins. Based on the observation of strong chemical variation and strong alkali enrichment, the chemistry of the Stikine belt volcanics is consistent with a rift-type environment. Souther (1977) has emphasized that the distinct changes in late Cenozoic volcanism along tectono-stratigraphic belts of the Cordillera indicates that extrapolation of tectonic environments cannot be made along the length of the Canadian Cordillera.

This discussion of the Heart Peaks volcanics will outline the petrogenesis within the framework of the Stikine belt volcanics, emphasizing the relationship to other centres such as Level Mountain and Mt. Edziza.

CHAPTER III

COMPARATIVE MAGMATISM

A summary of tectonic environments and magmatic associations seen in well known centres of Cenozoic, continental alkaline volcanism will be useful in gaining a frame of reference within which the Heart Peaks volcanics may be considered. The regional significance of alkali olivine basalt magma in northern British Columbia may be evaluated if comparisons with similar centres of volcanism can be seen to be valid.

Features which have been found to be common factors influencing regions of continental alkali basaltic volcanism include thin continental crust, high heat flow, tensional tectonic regimes, and often, spatial and secular variations in magma compositions. In most cases, the dominant element which controls volcanism is lithospheric structure. Thin continental crust, in the order of 25 to 35 km thickness is typical of the Basin and Range Province of western U.S.A., (Leeman and Rogers, 1970; Scott et al., 1970; Cook, 1969) and the northern part of the East African Rift and the Afar region, (Barberi et al., 1975; Mohr, 1968; De Fino et al., 1973). The combination of tensional tectonic elements associated with local thinning of continental crust in these magmatic provinces is strong evidence that the structure of the lithosphere may be the most important control on the site and character of volcanism as suggested by Bailey (1976). Though detailed geophysical data on the crust of northern British Columbia east of the Queen Charlotte Fair-

weather Fault system is lacking, the crust is thought to be relatively thin beneath the western Cordillera compared to areas further east where Phanerozoic rocks are thought to be underlain by Precambrian basement. White et al., (1968) indicate that crustal thickness may be of the order of 30 km in central British Columbia.

Graben-like depressions and normal faulting as seen in the East African Rift, the Tertiary and Quaternary magmatic province of France and central Europe (Wimmenauer, 1969) and eastern Australia (Wellman and MacDougal, 1974; Wilkinson, 1968) is a reflection of the regional tensional tectonic environments, causing volcanism to occur in narrow linear belts. Volcanism in eastern Australia may have migrated eastward over time, but single episodes of activity occurred in generally north-south trending belts. With respect to the tectonic regime of northern British Columbia, Souther (1977) has emphasized the linear distribution of late-Tertiary and Quaternary eruptive centres of the Stikine Belt and that tensional forces may be related to right lateral movement which is occurring on the Queen Charlotte-Fairweather Fault system to the west. In the Edziza Range north-south normal faulting is known to have been active during the period of volcanic activity (Souther and Symons, 1970). At Heart Peaks, there is no evidence for contemporaneous faulting and volcanic activity, but the occurrence of consistently north-south trending basaltic dykes suggests that some crustal element may have influenced fissure type activity.

The association of alkali basaltic volcanism with the continental rift type environment is seen to be strongest in the East African Rift. Compositional variation of magma type appears to change from tholeiitic in the Red Sea-Gulf of Aden region to progressively more alkaline compositions towards the south in Ethiopia and Kenya. Tholeiitic basalts are found associated with alkali basalts in most examples of rift environments but normally tholeiites are subordinate in volume. In the Basin and Range Province, eastern Australia and the Baikal Rift, contemporaneous alkaline and tholeiitic rocks have been suggested by most investigators to be associated with a common parent. Strong bimodality in silica contents is often characteristic of the mildly alkaline basalt - trachyte - alkali rhyolite suites. The Gregory Rift and the Kenya Rift valley of eastern Africa illustrate the bimodal character of the alkaline suites and the great volumes of peralkaline silicic lavas relative to associated alkali basalt (Baker, et al., 1972, 1977). Carmichael, et al., (1974) stresses that it is not unusual to find one or more chemically distinct series closely associated with the alkali basalt - trachyte series such as tholeiitic rocks of the central European province and strongly undersaturated rocks in the Kenya Rift.

Compositions in the Level Mountain and Mt. Edziza Ranges exhibit a range from primitive alkali basalt to peralkaline rhyolite and trachyte. Peralkaline silicic rocks occur interlayered with basalt and as domes and subvolcanic intrusions. At Heart Peaks a similar extreme range of silica values occurs, however the silicic rocks are not

peralkaline varieties. Rhyolites of the Heart Peaks Formation appear to have a calc-alkaline affinity.

The close association of continental alkali basalt volcanism with tensional tectonic regimes seen in many Cenozoic volcanic centres allows some parallels to be drawn regarding volcanism and its relationship to tectonism in northern British Columbia. Souther (1977a) considers that the spatial distribution of late Cenozoic eruptives in the north-south trending Stikine belt together with the distinctive alkali basalt - trachyte - alkali rhyolite magma association can be favourably compared with other similar tectono-magmatic associations. The present day tensional forces thought to be affecting the Stikine belt may be indirectly related to right lateral shear occurring along the Queen - Charlotte fault, the boundary between the Pacific and North American plates.

CHAPTER IV

FIELD MAPPING

Introduction

Field mapping was begun in the summer of 1976 with the following objectives:

i) To map the areal distribution of rock types.

ii) To determine the volcanic stratigraphy.

iii) To describe the physical volcanology, age relationships and glacial features.

iv) To collect samples.

Location and Access

The Heart Peaks area is accessible by helicopter from Dease Lake, B.C., 80 miles to the east. The only access to the area by land is via the old Telegraph Trail which follows the valley of the Dudidontu River to the east of the plateau. The trail can be followed on horseback from Sheslay, southeast of Heart Peaks, where there is a small airstrip available for fixed wing aircraft.

A camp was set up at a centralized location on the Heart Peaks plateau from which traverses could be run to various locations. Most work was concentrated on the western edge of the plateau where thick volcanic successions are exposed and the widest variety of lithologies is present.

Physiography

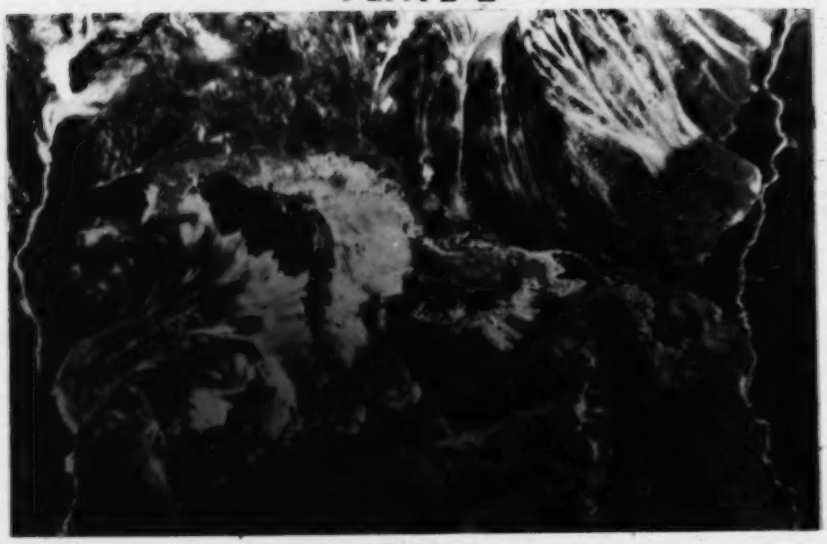
The basic volcanics at Heart Peaks have formed a flat-topped plateau which rises roughly 900 metres above the local topography. The twin Heart Peaks, centrally located on the plateau, are columnar jointed volcanic flows which rise about 200 metres above the plateau (Plate 3). The plateau is sharply dissected on all sides by fast flowing streams. The Dudidontu river on the east and the Sheslay River to the west follow gently sloping valleys north into the drainage system of the Nahlin and Inklin Rivers. The erosional pattern of the volcanics is determined largely by the flat-lying, columnar-jointed nature of the flows. Massive landslides have resulted in the destruction of large sections of the edge of the plateau. The Sheslay slide described by Souther (1971) resulted in the flowage of great volumes of debris into the Sheslay valley to the west (Plate 2). The acid volcanics on the western side of the plateau have a distinctly different weathering pattern, which reflects the morphology typical of flows of acidic composition. These very viscous lavas have built steep-sided brightly colored domes. The very coarse, angular debris forms unstable talus slopes. Continuous movement of these unstable slopes develops rock glaciers, a distinctive feature seen on the edges of the acidic domes (Plate 2).

The acidic rocks show little evidence of glaciation, however it is doubtful that any traces would be preserved due to the rapid rate of erosion. The top of the basaltic plateau bears evidence of continental

A. Aerial photograph of the erosional pattern of rhyolite. Rock glaciers can be seen on the upper left and lower right.

B. Aerial photograph of the location of the Sheslay Slide which has exposed basalt flows of the Level Mountain Group.

PLATE 2



A

B

glaciation. East-west striking glacial striae can be seen on flow surfaces and glacial till deposits several feet thick can be found. Glacially drifted material includes granitic and ultramafic boulders which must have been transported from several miles away.

Basement Geology

The Cenozoic volcanics at Heart Peaks lie unconformably on deformed Jurassic sediments of the Takwahoni and Inklin formation which represent contemporaneous near shore and far shore facies derived from source rocks to the southwest. The Jurassic sediments overlie, sometimes conformably, Upper Triassic andesitic volcanics of the Stuhini Group. Figure 3 shows a map of the geology in the Heart Peaks area from the Tulsequah and Dease Lake sheets (Souther, 1971; Gabrielse and Souther, 1962). These rocks have been deformed into west-northwesterly trending folds in middle Jurassic times when uplift occurred in the coast mountains to the southwest and in the Atlin Horst in the northwest. In general the Mesozoic rocks lie in a belt on the western side of the Intermontane belt of the Canadian Cordillera: thus Heart Peaks sits astride the western boundary of the Intermontane belt.

Brief consideration of the dominant structural elements of the pre-Cenozoic rocks may be useful in assessing any possible relationship between the older structural grain of the crust and late Cenozoic volcanism in northern British Columbia. Figure 2 shows the location of late Cenozoic volcanic centres and the major faults and lineaments of British Columbia. The dominant structural trends in northwestern

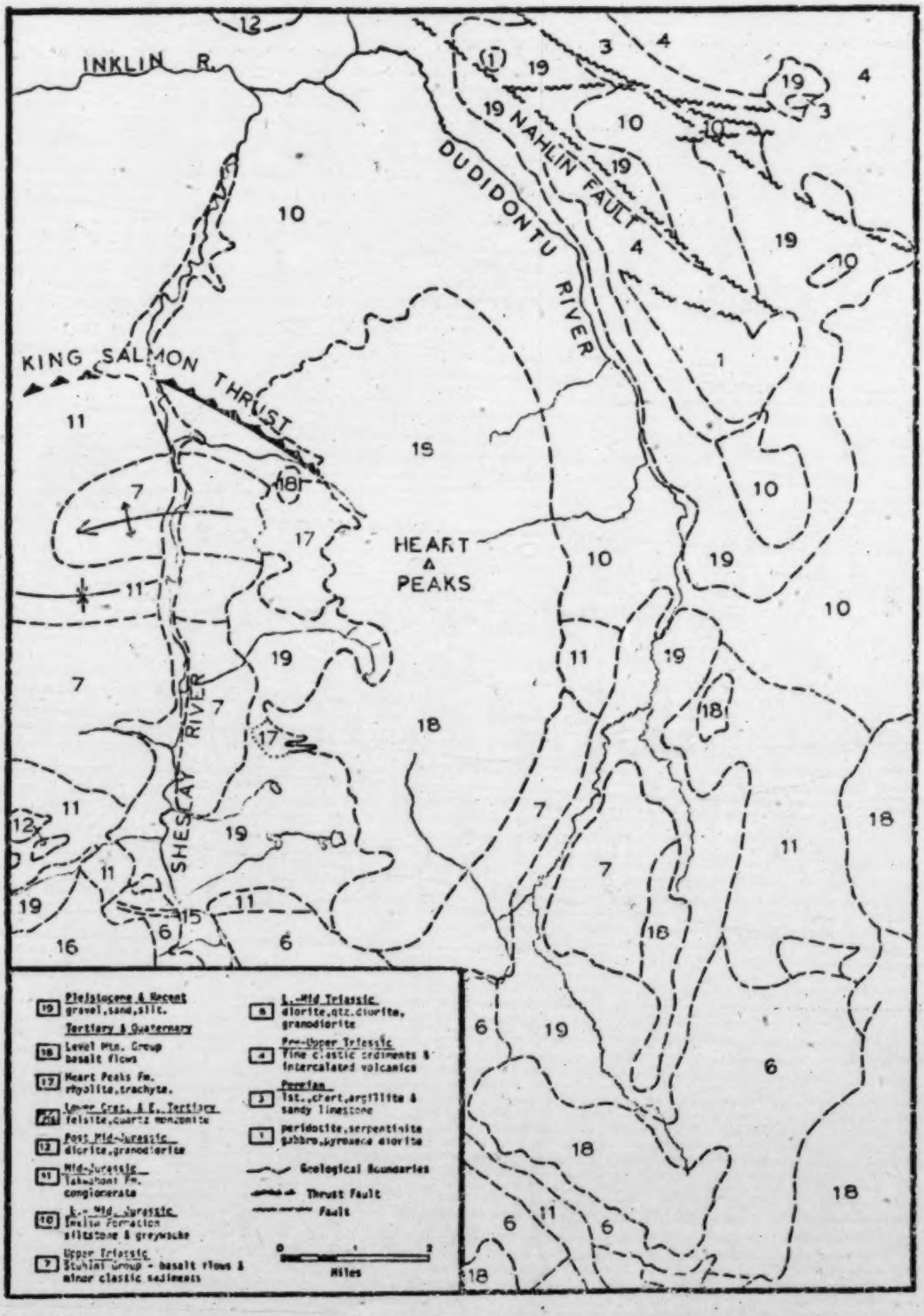

INKLIN R.
DUDIDONTU RIVER
NAHLIN FAULT
KING SALMON THRUST
HEART PEAKS
SHESLAY RIVER
Pleistocene & Recent gravel, sand, silt.
Tertiary & Quaternary
Level Mtn. Group basalt flows
Heart Peaks Fm. rhyolite, trachyte.
Lower Cret. & E. Tertiary felsite, quartz monzonite
Post Mid-Jurassic diorite, granodiorite
Mid-Jurassic Takahoni Fm. conglomerate
L.- Mid. Jurassic Inklin Formation siltstone & greywacke
Upper Triassic Stuhini Group - basalt flows & minor clastic sediments
L.-Mid Triassic diorite, qtz. diorite, granodiorite
Pre-Upper Triassic fine clastic sediments & intercalated volcanics
Permian lst., chert, argillite & sandy limestone
peridotite, serpentinite gabbro, pyroxene diorite
Geological Boundaries
Thrust Fault
Fault
Miles

Fig. 3. Generalized geology of Heart Peaks and surrounding area.

British Columbia are a series of west-northwesterly trending thrust faults and normal faults which are parallel to regional fold trends. Though southward thrusting of perhaps a minimum of 10 miles occurred on faults related to the Atlin horst in Upper Jurassic time (Souther, 1971), there is no evidence that any movement has occurred since Upper Tertiary time. The Nahlin fault, which bounds the Atlin horst to the north of Heart Peaks appears to have been a deep fracture along which ultramafic bodies were emplaced in Permian time. It has been suggested that the King Salmon thrust fault is a deep fracture similar to the Nahlin fault (Gabrielse and Wheeler, 1961) or a fault conformable to the Triassic sediments (Souther, 1971). A comparison of the trends of late Tertiary and Quaternary volcanics in northern British Columbia with the older dominant structural elements does not suggest any relationship between the volcanic centres running north-south and most pre-existing structures running east-west. The period during which the greatest amount of movement took place on these lineaments did not produce any volcanism at the surface and they are unlikely to have influenced the latest period of volcanism. If, as suggested by Bailey (1977), the location of intracontinental volcanism is controlled primarily by crustal structural elements, then some north-south trending structural element must play an important role. Evidence from the Edziza Range (Souther, 1970) suggests that since Miocene times volcanism may be related to normal faults, the result of

crustal extension.

Cenozoic Volcanics: General Statement

Figure 4 shows the distribution of the two distinctive volcanic units represented in the Heart Peaks area and the location of eruptive centres and linear dykes. The formation names, which have been taken from Souther (1971) emphasize a compositional distinction between rock units rather than a time-stratigraphic one.

The eruption of the volcanics began on a relatively flat Jurassic erosional surface and the initial period of activity may have included eruption of lavas representative of both map units. The field characteristics of the two units will be discussed separately, as they represent contrasting eruptive styles and chemical compositions: see Plate 3.

Level Mountain Group

Texturally the rocks of the Level Mountain Group are very similar to the flows of the vast Level Mountain Range located about 16 km to the east. It would be an oversimplification to consider the flows of the Heart Peaks area as merely an outlier of the Level Mountain plateau, as local eruptive centres are obvious and chemical differences are apparent between the two centres (personal communication T. S. Hamilton).

The rocks outcrop as flat-lying flows and pyroclastics. The southwestern edge of the plateau shows a virtually uninterrupted vertical sequence of about 600 metres of basaltic flows. Textural variations throughout the entire section are generally very subtle. Pillow lavas

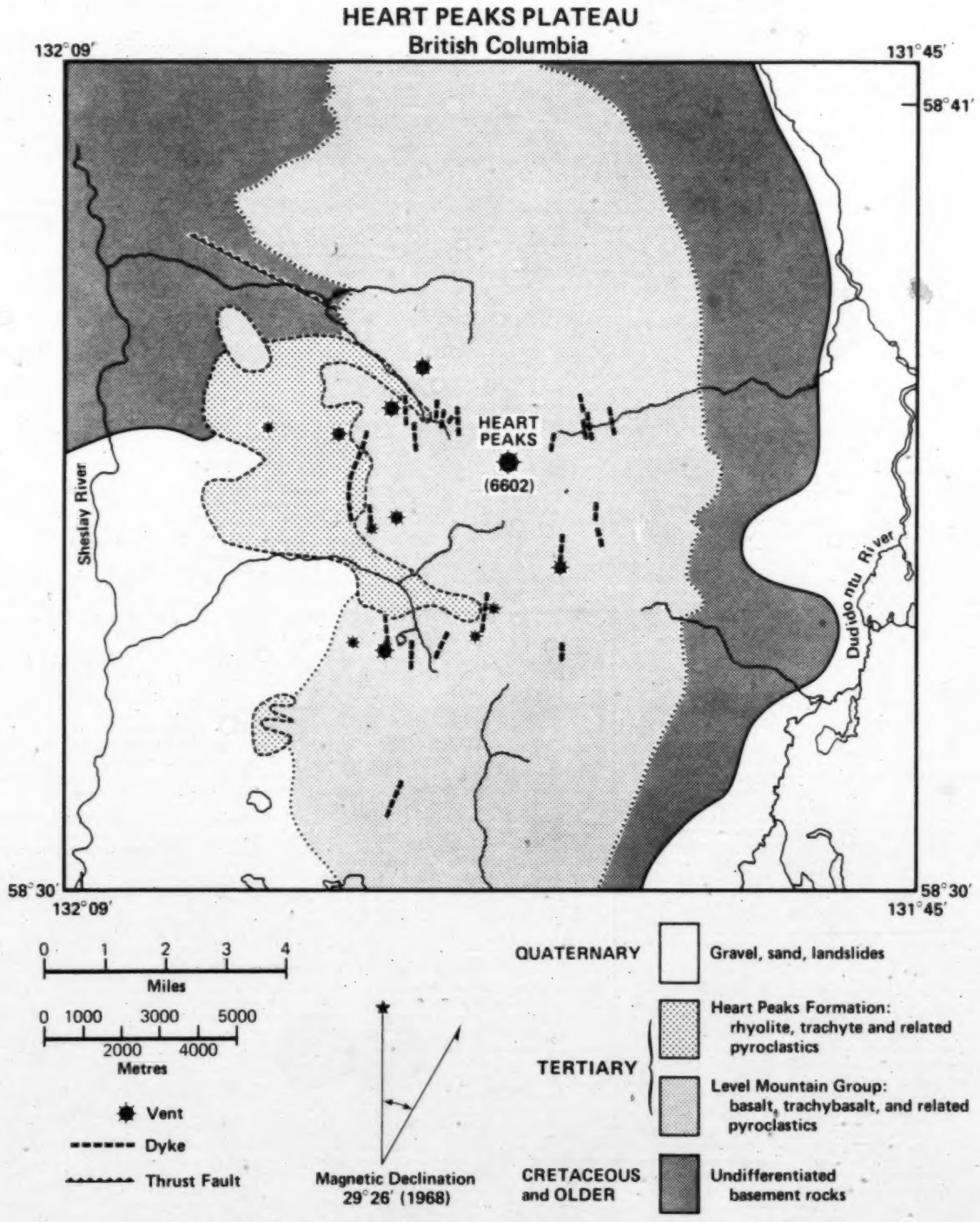


Fig. 4. Geology of the Heart Peaks area.

A. Rhyolite domes, Heart Peaks Formation.

B. Plateau basalts, Level Mountain Group.

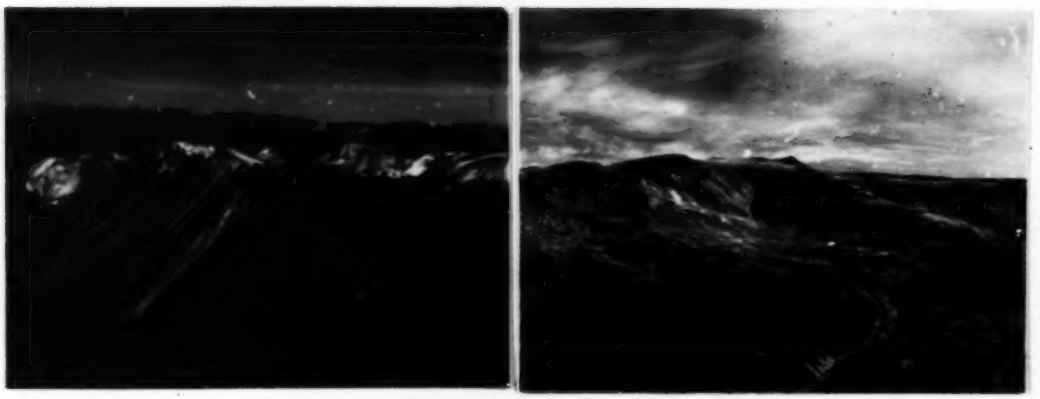
C. Columnar jointed flows, Level Mountain Group.

D. Vent agglomerate (right) cutting tuffs (left).

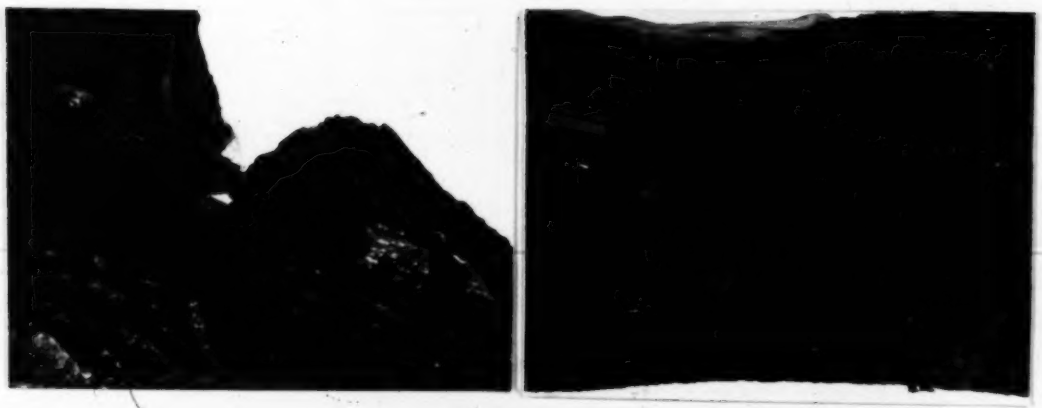
E. Pyroclastic breccia, Heart Peaks Formation.

F. Pyroclastics, Level Mountain Group.

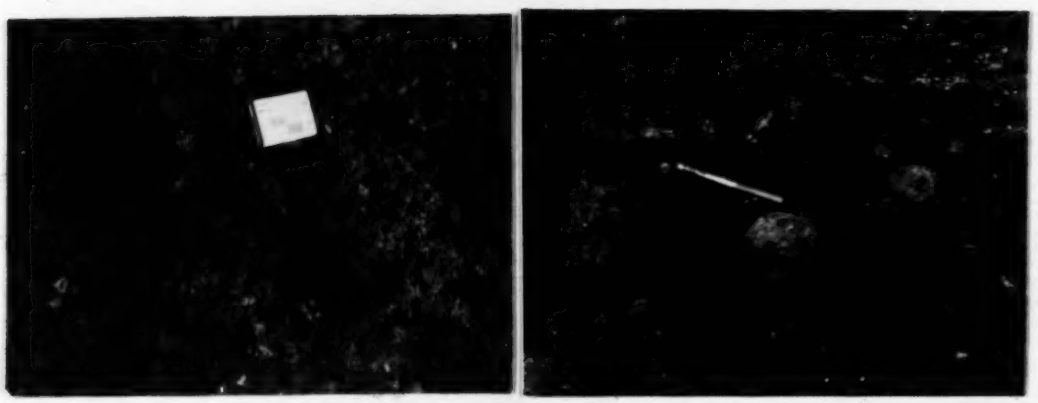
PLATE 3



A B



C D



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are found in several locations throughout the sections. Their very localized nature suggests that the flows encountered small lakes or rivers on the surface. Locally some flows show a loose, rubbly weathering pattern which may indicate that the lavas have flowed onto ice.

The main textural varieties of basaltic flows are:

1) Fine-grained plagioclase phyric basalts. Feldspar crystals are less than five mm in size and make up less than five percent of the rock.

2) Plagioclase phyric basalts with crystals often larger than five mm and may comprise more or less than five percent of the whole rock.

3) Sub-ophitic medium grained basalt.

4) Scoria.

Figure 5 shows a generalized stratigraphic column. The thickness of flows average four to six metres and they commonly show well developed columnar jointing. Subangular conglomeratic deposits are found near the base of the section. These deposits contain boulders of both acid and basic volcanics suggesting that these types were both erupted in the early stages of activity, though probably from separate vents. Interlayered acidic and basaltic rocks are found only once, near the base of the section. The sub-ophitic variety is found near the base of the section and it may represent an intrusive sill rather than a flow. Fine grained plagioclase phyric flows dominate the section. Individual flows typically have a red weathered, scoriaceous layer near the top. The rubbly top grades downward to a less weathered scoriaceous layer

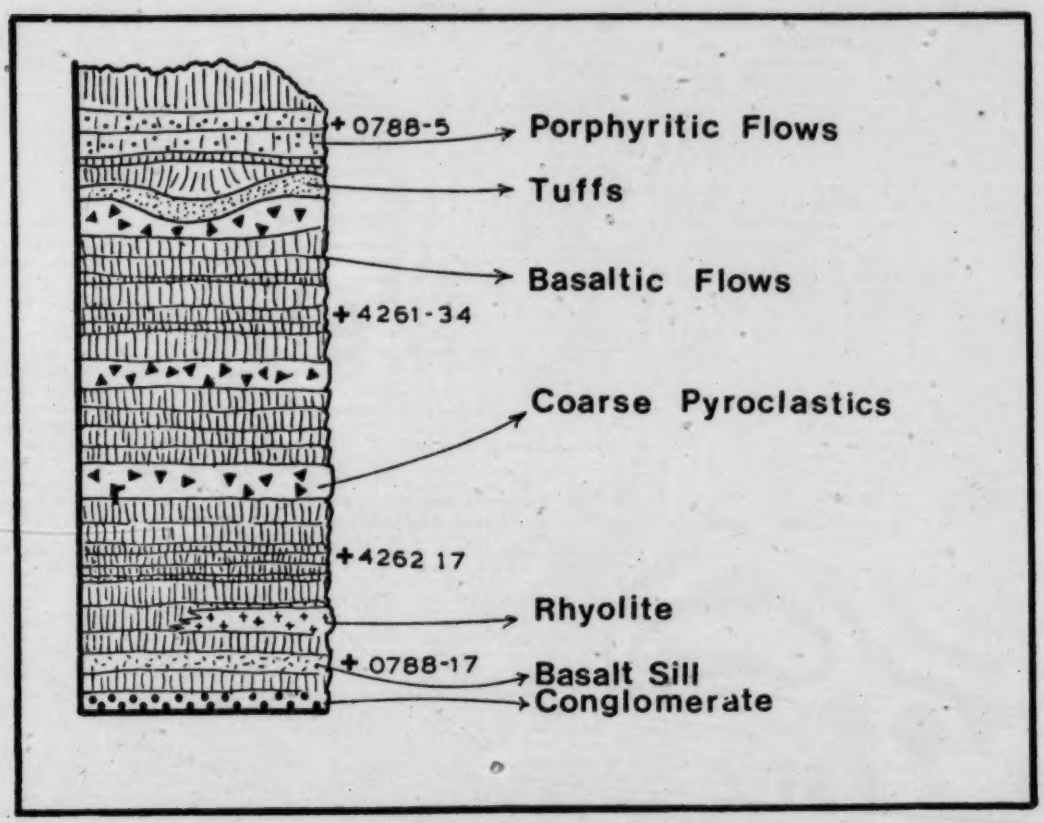


Fig. 5. Generalized stratigraphic column of the Heart Peaks volcanics. Numbers indicate representative chemical analyses.

and finally to massive columnar jointed basalt. The southwestern edge of the plateau (Plate 2) exposes about 25 individual flows typical of this description. These flows are sometimes interrupted by layers of agglomeratic pyroclastic.

The central area of the Heart Peaks plateau shows the most complex and varied volcanic stratigraphy. The frequency of vent agglomerates is much higher near the centre of the plateau, suggesting that this area was the dominant centre of extrusive activity. The flat lying flows are interrupted in numerous locations by vents of pyroclastic debris. The flows commonly show irregular changing attitudes, having been influenced by the variable local relief to be expected in the most active areas.

The plagioclase phyric basalts, containing large phenocrysts, occur in the upper several hundred feet of the succession. The plagioclase phenocrysts are of all sizes, commonly larger than five mm. The groundmass of these flows is grey in color and their composition is generally in the range of hawaiite.

The evolution of the Level Mountain Group lavas which formed the volcanic plateau may be divided into two stages. The initial plateau building period was characterized by dominantly fluid lava flows. The last 150 m of the succession appears to have been produced after an erosional interval. An erosional period is suggested by the existence of shallow u-shaped valleys which cut into the underlying flows, and thick, localized beds of volcaniclastic sediments. These sand sized

palagonite tuffs have been transported short distances by water. They form lens shaped deposits between flows and are locally 40 metres thick. The fragments are all of volcanic origin and show a very consistent graded bedding ranging from one centimetre sized pebbles to coarse sand sized, subrounded fragments. The fragments include pieces of fine grained scoriaceous basalt and grains of hornblende and pyroxene.

The uppermost flows, which complete the volcanic succession, were erupted after this erosional interval and generally represent more evolved compositions compared to the lower basaltic flows.

Two contrasting eruptive styles are obvious in the Level Mountain Group rocks:

1) Explosive pyroclastic activity (represented by tuffs and agglomerates).

2) Fluid fissure type eruptions (represented by flows and long, linear dykes).

The fissure type eruptions occurred from local vents and from long linear fissures represented by basaltic dykes. Almost all (90%) of the dykes strike in a north south direction and sometimes they may be traced for two to four km along strike. This linear distribution of dykes may be a reflection of local structural trends. No structural offsets appear to have affected the volcanic succession along this trend. The dykes are texturally and compositionally similar to the flows that they intrude. Commonly they are about four metres wide and show well developed lateral cooling joints. The remains of the more re-

sistant dykes often project prominently above the surrounding flows.

The undisturbed state of some of the uppermost flows is illustrated by the presence of lava tubes. These concentrically layered structures indicate prolonged flowage through a pipe-like conduit. Gradual inward cooling results in the preservation of a concentric structure.

The central part of the plateau contains the most abundant pyroclastic deposits indicative of local, high energy explosive eruptions. Flows and pyroclastic debris are closely associated in the eruptive centres. Features common to most of the vents shown on figure 4 allow a generalized cross section to be constructed which may be considered typical of the vents (Figure 6). The twin Heart Peaks, the highest points on the plateau, are similar to this section. The domes are flanked by vent breccias deposited around a central jointed lava dome. Underlying flows can be seen to be bent upwards by the intruding lavas and pyroclastics.

The vent breccias (Plate 3) often carry massive boulders of the order of one metre across. The angular unsorted fragments are remnants of previously solidified flows and blocks of scoria. It appears that the explosive eruptions served to open the vent, through which the later fluid lavas were extruded. The contacts between vent breccias and intruded flows or pyroclastics are relatively abrupt.

The morphological contrast between the Level Mountain Group rocks and those of the Heart Peaks Formation is the result of the

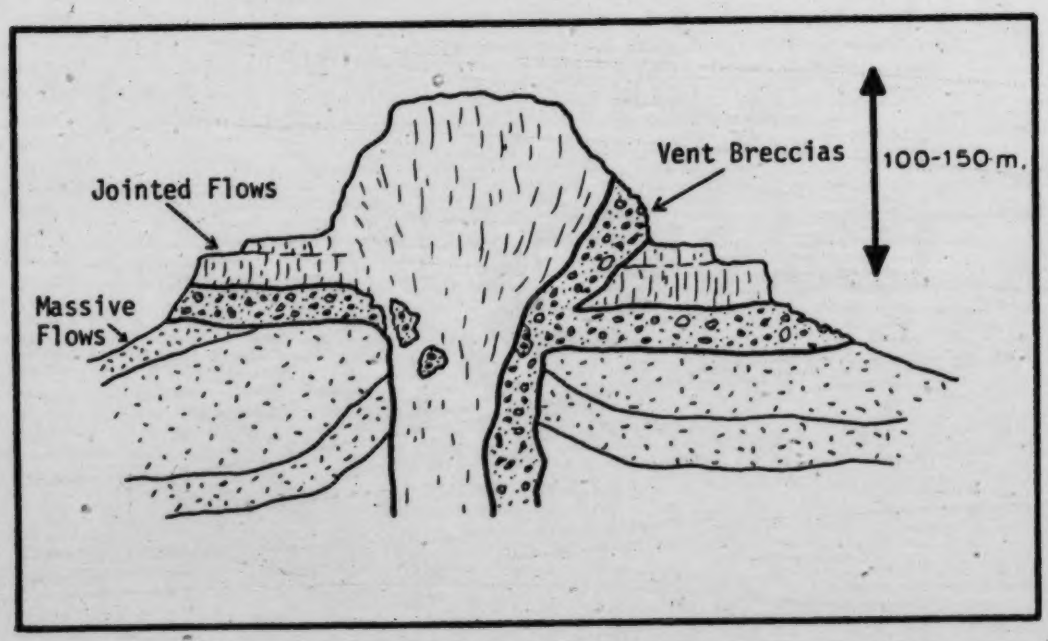


Fig. 6. Generalized cross-section of a vent on the Heart Peaks plateau.

contrast in composition between the two units. Fissure type lavas form plateaux of great areal extent and are with few exceptions, composed of basaltic rocks. The low viscosity of the lava and the linear conduits from which it rises allow great thicknesses to be built by successive flows.

Numerous foreign fragments are found in the Level Mountain Group flows and pyroclastics. These include:

1) Megacrysts of olivine and kaersutite.
2) Gabbroic inclusions.
3) Pyroxenite inclusions.
4) Alkali diorite inclusions.

The commonest inclusions are black vitreous amphibole fragments which can be as large as ten cm across. Resorption of the crystals by the enclosing lava is common and the inclusions have the appearance of conchoidally fractured glass. The morphological evidence indicates that these inclusions are not in equilibrium with the host lavas. Evidence bearing on the origin of these inclusions will be discussed later. The rare pyroxenite inclusions are found in basaltic flows. Their mineralogy and petrological significance will be discussed in a later chapter.

Heart Peaks Formation

The rocks of the Heart Peaks Formation outcrop on the western side of the Level Mountain Group flows. The composition of the Heart Peaks Formation rocks is reflected in their unique eruptive styles.

The high viscosity of these acidic lavas has resulted in the formation of steep sided domes in which individual flow units are scarcely recognizable. One of several individual domes, which form prominent ridges may be seen in Plate 1.

This unit is composed of rhyolite, dacite, and trachyte flows and related pyroclastic rocks. There is a wide variety of textures, including thinly laminated flows, prophyritic flows, crystal tuffs, ash flow tuffs, and unconsolidated tuff deposits. Trachyte and dacite occur as light grey to brown flows. Porphyritic flows are common in which phenocrysts compose 30-40%. These flows were likely to be extremely viscous upon eruption, resulting in extensive auto brecciation of the flows. Phenocrysts include quartz, sanidine and anorthoclase. There appears to be two generations of phenocrysts to be seen in hand specimens. Extensively altered phenocrysts coexist with very fresh sanidine phenocrysts. Sutured and annealed boundaries suggest that the altered phenocrysts may be xenocrysts.

Fine grained pyroclastics are exposed as a complete section which grades from unconsolidated ash downwards to fine grained moderately consolidated tuffs and finally to dark, red-brown, ash flow tuffs. Flattened pumice fragments are evidence of viscous flow and plastic deformation after partial consolidation of the pyroclastics. Local large scale cross bedding of pyroclastics indicates the strong influence of either local wind directions or differing directions to the source of explosive activity.

Coarse pyroclastics are uncommon in the Heart Peaks Formation rocks but they do occur as angular breccias.

Age Relationships

In the absence of any radiometric ages for the volcanics at Heart Peaks, one is forced to rely on geomorphologic and stratigraphic evidence to correlate the volcanic sequence with other centres and place the rocks in a proper time frame.

Souther (1970) emphasizes two fundamental periods of change in the character of volcanicity during Cenozoic time in the northern cordillera. Quiet effusion of alkali-olivine basalt began in central British Columbia after the cessation of explosive acidic volcanism of the Sloko Group. Upper Miocene ages (K-Ar) have been obtained on basaltic dyke swarms which may represent feeders to these early plateau basalts (Symons, 1969). After the onset of the plateau building alkalic lavas, the eruptive style changed, in the late Miocene, to central volcanic eruptions of more evolved and varied magma types. The basalt plateau at Level Mountain, Mt. Edziza and Heart Peaks are relatively small shields in comparison to those of south-central British Columbia which represent the great volumes of lava produced in the early plateau building period. The upper parts of the succession at Edziza, and the central acid, peralkaline rocks at Level Mountain centre may be representative of the latest phase of varied, sporadically erupted lavas. This phase of activity has continued until recent time, with the youngest eruptives being no more than a few hundred years old (Souther, 1970).

Radiometric dates indicate that the Mt. Edziza range was built over a span of 6 million years (Souther and Symons, 1974), beginning at approximately 6.1 million years B.P. The latest flows at Heart Peaks appear to have been erupted in the Pleistocene. Glacial striae on flows and till deposits beneath the uppermost flows suggests at least syn-glacial and possibly some post-glacial activity at Heart Peaks. The eruptive history of the Heart Peaks centre probably spanned a roughly comparable time period to other centres in the region and is representative of the time frame which in other parts of British Columbia saw the eruption of alkaline lavas of varied composition.

Conclusions

Field evidence suggests that the Heart Peaks Formation rocks and those of the Level Mountain Group were not erupted from the same vents. Vent agglomerates do not contain fragments of both units. Contacts between the two units are obscure but appear to be almost vertical (Plate 1) and interlayering of the two units was seen only once in a limited exposure. Evidence has been given that indicates that the earliest eruptive activity included lavas of both Heart Peaks Formation and Level Mountain Group. Plate 1 illustrates the contact between the units. The uppermost Level Mountain Group flows appear to be stratigraphically above the Heart Peaks rocks. Late stage basaltic dykes can be seen cutting both units.

While the Level Mountain Group rocks show many similarities to those at the Level Mountain Range to the east (Hamilton and Scarfe,

1977), the non-peralkaline silicic rocks of the Heart Peaks formation offer numerous contrasts to the abundant peralkaline flows at Level Mountain. The absence of any alkali-ferromagnesian minerals such as aenigmatite, aegirine-augite, riebeckite and arfedsonite in the Heart Peaks Formation rocks suggests a less enriched sub-alkaline affinity in contrast to the peralkaline salic rocks at Level Mountain. In the Heart Peaks area, the two rock units are closely related in both space and time, thus a more complex investigation of the relationships necessitates a detailed chemical and petrographical study.

CHAPTER V

PETROGRAPHY

General Statement

This discussion will emphasize the mineralogical classification and textural variations of the Heart Peaks volcanics. General descriptive petrography is presented while specific mineralogical details and arguments will follow in a later chapter. The classification scheme relied upon is that of Irvine and Baragar (1971). Representative textures of volcanic rocks are shown in Plate 4.

Level Mountain Group

One of the major criteria in the distinction between the tholeiitic and alkali basalt rock series is the presence or absence of a reaction relationship between olivine and calcium-poor pyroxene. The alkali-olivine basalt series characteristically contains calcium rich augitic pyroxene which is often titaniferous, while calcium poor pyroxene is typically absent (MacDonald and Katsura, 1964). Using these criteria, the rocks of the Level Mountain Group belong to the alkali basalt series. The basaltic end members of this series are most abundant, while the felsic members, mugearite, benmorite and trachyte are rare. Although some rocks can be classified on the basis of chemistry as tholeiitic or calc-alkaline, the mineralogy is consistently indicative of the alkaline series. The most mafic flows are ankaramite, rich in titaniferous augite. Alkali-olivine basalt and hawaiites are volumetrically the most

A. Ankaramite from the Level Mountain Group with large subhedral, strongly zoned clinopyroxene and smaller corroded olivine phenocrysts. Fine groundmass contains clinopyroxene, olivine, plagioclase and titanomagnetite. Crossed polars.

B. Pyroxenite inclusion from the Level Mountain Group composed predominantly of fractured clinopyroxene (grey) and interstitial opaque oxides (black). Crossed polars.

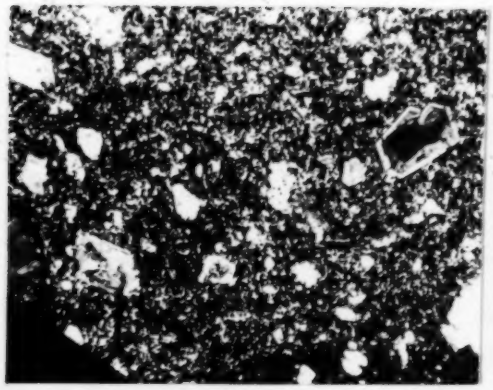
C. Alkali basalt from Level Mountain Group showing typical pilotaxitic texture with subhedral plagioclase (labradorite) laths, groundmass olivine, titaniferous clinopyroxene and euhedral grains of titaniferous magnetite. Crossed polars.

D. Ophitic texture in basalt with plagioclase and opaque oxides surrounded by clinopyroxene. Crossed polars.

E. Typical flow texture of andesite from Level Mountain Group composed predominantly of plagioclase in groundmass and as sparse microphenocrysts. Crossed polars.

F. Corroded quartz and sanidine phenocrysts in a glassy matrix in spherulitic rhyolite from the Heart Peaks Formation. Crossed polars.

PLATE 4



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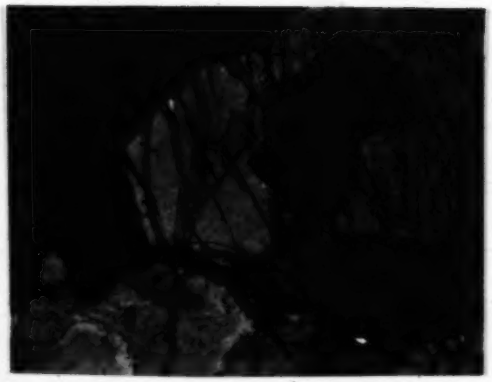

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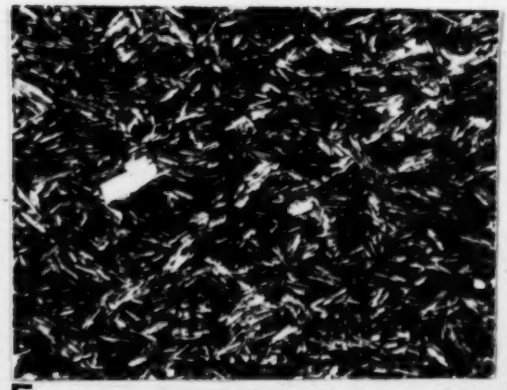

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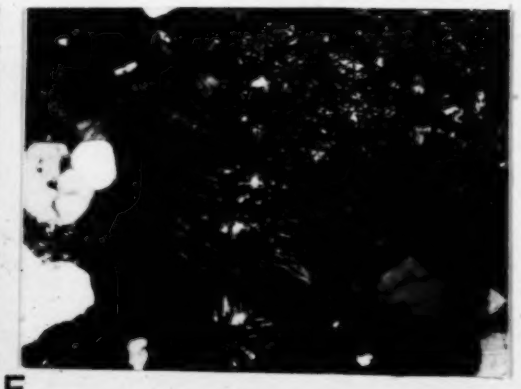

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important rocks, while the more potassic trachybasalts are less common.

Ankaramites

This rock type is particularly rich in augite and olivine phenocrysts and poor in plagioclase, which is restricted to the groundmass. Subhedral to euhedral augite crystals are strongly zoned with light brown and green interiors and pink Ti-rich borders. The Ti-rich border is often separated from the core of the crystal by a fine line of minute opaque inclusions. Mg-rich olivine is generally subordinate to clinopyroxene. Titanomagnetite, minor spinel, plagioclase, olivine, augite and minor glass make up the matrix. Opaque oxides are very abundant in these rocks, sometimes reaching twelve to fifteen percent. Ankaramites do not occupy a unique position in the stratigraphic succession, being found low in and midway through the sequence.

Alkali-Olivine Basalt

Alkali-olivine basalt is an important rock type in the Level Mountain Group and throughout northern British Columbia. At Heart Peaks it may be volumetrically subordinate to hawaiites, but its importance as a regional magma type must be stressed. Textural varieties which exist include subophitic, pilotaxitic and porphyritic. These textural varieties are also seen in hawaiite and trachybasalt, which appear to have been extruded in distinct pulses in the stratigraphic succession. The textural variations may be representative of subvolcanic magma conditions.

Pilotaxitic texture is common in the fine grained rocks which

make up the bulk of the plateau. Plagioclase and olivine occur as sparse phenocrysts in a flow oriented matrix dominated by plagioclase and interstitial titanaugite and titanomagnetite. These flows were probably very fluid when erupted and spread over long distances and rapidly built the lower plateau sequence.

Sub-ophitic alkali basalts contain crystals of sodic labradorite, partially enclosed by pink titanaugite. Olivine is usually present (5-8%) and varies from fresh euhedral crystals to corroded and altered ones. Phenocrysts of plagioclase show a complex pre-eruptive history. The crystals are complexly zoned and commonly contain zones of groundmass inclusions. Corrosion of phenocrysts is common. Textures indicate that olivine crystallized first as phenocrysts, followed by plagioclase, which was in turn closely followed by the simultaneous crystallization of pyroxene and ilmenite. Sub-ophitic basalt may be representative of shallow intrusive sills which could not reach the surface after the initial period of rapid plateau building.

Porphyritic basaltic rocks generally occur near the top of the succession. Individual flows contain a great variety of phenocrysts of plagioclase of many varying shapes which may have crystallized from liquids of varying compositions.

Perhaps one of the most important features of the basaltic rocks is the variety of inclusions found in flows. Alkali basalt the world over typically carries a variety of xenoliths which may represent accidental material torn and transported from crust or mantle sources, or they may

be cognate material which has crystallized at depth. In any case inclusions may often be good indicators of the petrogenesis of the host rocks.

Hornblende inclusions in basaltic rocks are common and may be important with regards to the fractionation trend of the magma. Disequilibrium textures seen with these inclusions suggest that they have not crystallized directly from their host alkali basalt. Reaction textures seen in thin section and their great size variation (10 cm to 1 mm) indicate disequilibrium with the basalt liquid. The red-brown, moderately pleochroic crystals have strongly corroded rims marked by a halo of small opaque oxide grains. Hornblende of similar composition is found as a major groundmass constituent of andesite and is therefore indirectly related to the basaltic magma and is not a foreign, accidental inclusion.

Other inclusions which are considered to be cognate include gabbro and alkali-diorite. Alkali diorite nodules are commonly found in flows and pyroclastics. The nodules have a coarse grained granular texture composed of plagioclase (An 40), clinopyroxene, olivine, minor hornblende and alkali feldspar. Undulatory extinction in feldspars and deformation lamellae in olivine and pyroxene are evidence of strain, possibly caused by short term shock during pyroclastic explosions, although longer term tectonic stresses may not be entirely ruled out as a cause of strain. Titanaugite crystals show very fine exsolution lamellae indicating a slow-cooling history. Hematitic alteration is common around the rounded grain boundaries, particularly on olivine.

The mineralogy of alkalidiorite nodules suggests that they are a cognate phase, representing a slow-cooled equivalent of trachybasalt or hawaiite.

Mafic eruptives also contain nodules of pyroxenite, composed of slightly strained titaniferous augite, which shows some minor alteration to amphibole. Pyroxene grains are highly fractured and enclose interstitial opaque oxides. These nodules exhibit cumulate textures. Clinopyroxene is of a composition found crystallizing in alkali-basalts and hawaiites, thus these inclusions may be representative of a phase fractionating from Level Mountain Group magma.

Uncommon fragments of biotite schist found in basalts and quartz xenocrysts in andesite may be representative of metamorphic basement rocks.

Trachybasalt and Hawaiite

These rocktypes are considered by Carmichael et al., (1974) to be roughly equivalent terms for rocks with high alkali content ($Na_2O + K_2O$) and silica content near 50 percent. Irvine and Baragar (1971) divide the alkali basalt series into a sodic and potassic series which reflects the ratio K_2O/Na_2O. The importance of K/Na ratio of primitive basalts is that it may be an indicator of the nature and environment of source materials (Carmichael et al., 1974). Some oceanic alkali basalt associations may be distinguished by their K/Na ratios. The islands of Tristan da Cunha (Baker et al., 1964) and Gough (Le Maitre 1962), for example, show distinctly more potassic

compositions than St. Helena (Baker, 1969) and Tahiti (McBirney and Aoki, 1968). The petrographic distinction between the two series (sodic and potassic) is reflected in coexisting feldspar compositions. The sodic series (hawaiite) generally contains a single feldspar (labradorite) while the potassic series (trachybasalt) contains labradorite and minor amounts of alkali feldspar in the groundmass. The Level Mountain Group includes rocks belonging to both series.

Hawaiite and trachybasalt flows are often very rich in phenocrysts (up to 35%). Labradorite and andesine are the most common phenocrysts with minor olivine and pyroxene. The groundmass is generally pilotaxitic, with labradorite laths (60-70%), euhedral olivine (5%), augite (5-15%) and titanomagnetite (8-12%). Alkali feldspar sometimes occurs as square, euhedral groundmass crystals or microphenocrysts.

Intermediate Rocks

Intermediate to felsic rocks of the alkali basalt series are rare. Rocks with 59% or more SiO_2 generally are quartz normative. Two thin flows of calc-alkaline andesite were found on the western side of the plateau. They contain a fine grained groundmass composed dominantly of andesine, pargasitic hornblende and titanomagnetite. Pyroxene is generally absent and quartz occurs as xenocrysts in these flows. The occurrence of hornblende as a major groundmass phase in these rocks (30%) has important implications regarding conditions of the fractionating liquids. Hydrous conditions must have prevailed at this

stage and the hornblende may have subsequently contaminated more mafic lavas.

Pyroclastic Rocks

Pyroclastic rocks of the Level Mountain Group show generally uniform textures, the commonest type being a very coarse vent-agglomerate. The commonest fragments seen in the fine groundmass include:

1) Quartz sandstone and siltstone.

2) Crystal fragments of quartz, alkali feldspar and hornblende.

3) Glassy and crystalline alkali basalts, and hawaiites.

The sedimentary fragments are pieces of the underlying Takwahoni Formation, while the volcanic fragments represent essential basaltic magma and accidental inclusions of previously cooled basaltic flows.

Heart Peaks Formation

The volcanics of the Heart Peaks Formation, though closely related to those of the Level Mountain Groups, differ significantly in mineralogy and chemical trends. At the Level Mountain Range (Hamilton and Scarfe, 1977) silicic rocks occur as centrally located domes and flows of pantellerite and comendite, with relatively minor volumes of rhyolite and dacite. Peralkaline silicic rocks, however, are absent at Heart Peaks. The acid rocks of the Heart Peaks Formation lack alkali-ferromagnesian minerals typical of silicic rocks at Level Mountain and Mt. Edziza.

Trachyte

Grey and brown trachytic rocks with porphyritic textures outcrop in the brightly colored domes west of Heart Peaks. Fresh exposures are difficult to find as the rocks are hydrothermally altered and deeply weathered.

Potassic trachytes show two textural varieties which are distinguished by the structural state of the constituent alkali feldspars. Sanidine trachyte contains three to four mm sized phenocrysts of clear euhedral sanidine which sometimes occur as large glomeroporphyritic clots. The groundmass is composed of pilotaxitic feldspar microlites and fine devitrified glass. The mineralogy of these rocks is generally quite simple, containing alkali feldspar and minor pyroxene and magnetite.

The other variety of potassic trachyte is a medium grained orthoclase trachyte in which orthoclase may amount to 25% of the rock as phenocrysts. A mottled extinction effect is caused by patchy exsolution of an albite-rich phase from orthoclase. Orthoclase trachytes in which exsolution of feldspar is seen must have undergone a slower cooling history than sanidine trachytes. These are also two-feldspar trachytes as plagioclase, usually rimmed with alkali feldspar, is commonly present. Minor augite occurs as granular aggregates with plagioclase, indicating that contamination by more mafic rocks may have occurred.

Rhyolite

Rhyolite occurs as glassy and porphyritic flows and fine grained pyroclastics. Rhyolite is very poor in ferromagnesian minerals due, in part, to extensive hydrothermal alteration. Flows are thinly laminated and contain sanidine and quartz phenocrysts. Glassy flows contain abundant spherulites in the groundmass.

Rhyolite crystal tuffs have a fine grained felty groundmass of quartz and alkali feldspar and contain granular aggregates of alkali feldspar.

Tuffs are often poorly consolidated and lie in primary layered beds which are being rapidly eroded.

Conclusions

Representative modal analyses (Table I) clearly show the alkaline character of Level Mountain Group basaltic rocks. The dominance of titanium-rich clinopyroxene and the abundance of euhedral olivine crystals confirms that these rocks are members of the alkali olivine basalt series.

Inclusions in basaltic rocks are chemically and mineralogically related to the fine grained extrusives.

Intermediate and felsic members of the alkali basalt series are rare in the Level Mountain Group.

The flows of the Heart Peaks Formation are dominated by silica saturated trachyte and rhyolite. Crystal tuff and unconsolidated pyroclastic deposits are common and indicate the presence of a gaseous

environment associated with the acid magma.

An important feature of the rocks of the Heart Peaks Formation is their occurrence as significant volumes of silica-rich, subalkaline compositions which are closely associated with the alkaline series of the Level Mountain Group.

TABLE I

REPRESENTATIVE MODES AND TEXTURES OF VOLCANIC ROCKS

Rock Type	Ankaramite	Alkali Basalt	Hawaiite
Sample No.	4261-19	7786-2	7/3 - 1K
Map Unit	Level Mountain Group	Level Mountain Group	Level Mountain Group
		Labradorite - 6%	Labradorite - 5%
Phenocrysts	Augite - 5%	Olivine - 3%	Olivine - 3%
	Olivine - 2%	Augite - 1%	
Groundmass	Labradorite - 33%	Labradorite - 40%	Labradorite - 55%
	Augite - 40%	Olivine - 25%	Augite - 22%
	Olivine - 8%	Augite - 15%	Olivine - 7%
	Ilmenite - 12%	Ilmenite - 10%	Ilmenite - 7%
Textures	Microporphyritic	Porphyritic	Porphyritic
		Corroded plagioclase phenocrysts	Pilotaxitic

(continued)

Rock Type	Andesite	Trachyte	Rhyolite
Sample No.	7788-13A	7788-8	TOC
Map Unit	Level Mountain Group	Heart Peaks Formation	Heart Peaks Formation
			Quartz - 10%
Phenocrysts		Orthoclase - 10%	Sanidine - 5%
		Labradorite - 1%	
Groundmass	Quartz - 4%	Orthoclase - 73%	Quartz - 24%
	Andesine - 50%	Oligoclase - 10%	Sanidine - 40%
	Alkali Feldspar - 9%	Augite - 5%	Glass - 20%
	Hornblende - 30%	Ilmenite - 1%	Ilmenite - 1%
	Ilmenite - 10%		
Textures	Equigranular	Glomeroporphyritic	Porphyritic
		Pilotaxitic	

CHAPTER VI

CHEMISTRY

Major Elements

Major element analyses for ten oxides were run using X-ray fluorescence (Table II) and electron microprobe analysis on glasses (Appendix A). H_2O contents were determined independently by the Penfield method (Appendix C). Totals reported represent anhydrous analyses.

Classification

Chemical classification of the volcanics at Heart Peaks is illustrated using major element comparison diagrams. Figure 7, the alkalis versus silica diagram (MacDonald and Katsura, 1964; Irvine and Baragar, 1971) indicates that the basaltic rocks lie in the mildly alkaline range. The dividing line between alkaline and subalkaline (tholeiitic) is that of MacDonald and Katsura (1964). The inset compares compositions of alkaline oceanic suites with the dividing line proposed by Irvine and Baragar. The An - Ab - Or plot is used to subdivide the alkali basalt series into a sodic and potassic series. Alkali basalts, trachybasalts and hawaiites plotted on Figure 8 indicate the varying degrees of enrichment of sodium and potassium in these rocks. Figure 9 is a subdivision of the alkali basalt series based on normative plagioclase composition versus colour index. This plot reflects the dominance of alkali basalt and hawaiite, the relative scarcity of intermediate compositions and the

TABLE II

MAJOR AND TRACE ELEMENTS (XRF)

	1	2	3	4	5	6	7	8
SiO_2	46.52	47.66	48.02	49.09	49.24	49.61	49.82	49.96
Al_2O_3	16.52	16.05	15.67	16.08	16.82	16.54	16.52	16.67
Fe_2O_3	2.89	3.14	2.65	2.48	2.48	2.66	2.76	2.54
FeO	9.02	9.77	8.30	7.76	7.76	8.30	8.61	7.94
MgO	7.48	5.84	8.85	7.09	5.69	5.59	4.30	6.30
CaO	9.43	9.93	8.73	9.29	8.77	8.55	8.39	8.03
Na_2O	3.30	3.25	2.93	2.84	3.87	4.11	3.93	3.86
K_2O	1.09	0.89	1.32	1.43	2.14	1.05	1.57	1.45
TiO_2	2.71	2.68	2.45	2.38	2.15	2.81	3.07	2.24
MnO	0.18	0.19	0.19	0.15	0.18	0.17	0.20	0.18
P_2O_5	0.80	0.58	0.72	0.97	0.85	0.59	0.78	0.80
$H_2O^{(+)}$	-	0.87	3.4	4.8	2.10	2.22	-	-
Ba	605	373	650	1132	872	658	618	724
Nb	51	29	61	62	74	55	56	66
Zr	197	189	253	297	276	271	291	290
Y	27	32	28	29	26	33	42	29
Sr	712	524	654	971	837	558	608	647
Rb	22	13	23	22	48	14	30	30
Zn	73	100	73	70	82	76	98	80
Cu	62	43	64	71	54	57	49	44
Ni	123	37	125	82	81	39	22	70
Cr	295	56	259	160	257	52	23	107

(continued)

MAJOR AND TRACE ELEMENTS (XRF)

	9	10	11	12	13	14	15
SiO_2	50.66	52.87	51.86	53.15	59.71	60.41	76.01
Al_2O_3	16.56	15.58	16.90	16.31	14.75	14.76	13.20
Fe_2O_3	2.84	2.45	2.66	2.39	1.91	1.85	0.22
FeO	8.86	7.65	8.34	7.47	6.02	5.82	0.71
MgO	4.53	4.15	3.70	5.24	3.30	3.15	0.15
CaO	7.79	8.34	6.84	7.05	5.82	5.72	0.21
Na_2O	3.71	3.49	4.10	3.43	3.82	3.79	4.33
K_2O	1.61	2.53	2.19	2.28	2.56	2.57	4.84
TiO_2	2.25	2.12	2.40	1.86	1.51	1.50	0.24
MnO	0.20	0.22	0.18	0.17	0.11	0.10	0.01
P_2O_5	0.93	0.43	0.79	0.50	0.36	0.30	0.03
$H_2O^{(+)}$	1.49	3.40	2.4	3.10	-	-	1.30
Ba	721	605	668	595	342	277	93
Nb	65	41	74	41	80	68	133
Zr	328	245	348	245	192	187	896
Y	45	35	41	33	45	39	61
Sr	604	311	619	336	325	335	71
Rb	15	45	45	44	728	734	185
Zn	101	86	108	83	67	80	12
Cu	61	43	38	54	28	60	20
Ni	39	36	26	34	37	30	12
Cr	66	98	124	85	61	143	32
Total (Anhydrous)	100.14	99.98	100.17	100.01	100.07	100.16	100.10

(continued)

SAMPLE NUMBERS AND ROCK NAMES

1.	4261-6	Alkali Basalt
2.	4262-19	High Alumina Basalt
3.	7785-3	Tholeiitic Basalt
4.	4261-36	Tholeiitic Basalt
5.	7786-18	Alkali Basalt
6.	0788-3	Hawaiite
7.	4262-20	Hawaiite
8.	4260-2	Tholeiite
9.	1015-6A	Tholeiite
10.	0788-21	Andesite
11.	0788-2	Andesite
12.	0788-17	Tholeiitic Basalt
13.	7788-13	Andesite
14.	7788-13A	Andesite
15.	0789-5A	Rhyolite

TABLE II (cont'd.)

XRF ANALYSES NORMS

	1	2	3	4	5	6	7	8
Q	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Or	6.44	5.25	7.80	8.39	12.62	6.20	9.29	8.57
Ab	25.56	27.52	24.74	23.96	27.50	34.72	33.19	32.65
An	27.01	26.54	25.64	26.75	22.17	23.60	22.78	23.83
Ne	1.28	0.0	0.0	0.0	2.83	0.0	0.0	0.0
Di	11.79	15.55	10.38	10.32	12.85	12.22	11.26	8.74
Hy	0.0	2.99	7.26	15.65	0.0	1.90	5.55	5.16
Ol	16.54	11.07	13.37	2.94	12.12	10.71	6.06	11.11
Mt	4.19	4.54	3.84	3.58	3.59	3.85	3.99	3.67
Il	5.14	5.08	4.65	4.50	4.07	5.34	5.82	4.25
Ap	1.89	1.36	1.70	2.29	2.00	1.38	1.84	1.88
Py	0.17	0.08	0.62	1.62	0.25	0.08	0.21	0.13
Cor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

(continued)

XRF ANALYSES NORMS

	9	10	11	12	13	14	15
Q	0.0	0.35	0.0	1.10	10.59	11.64	31.42
Or	9.48	14.93	12.93	13.45	15.10	15.16	28.60
Ab	31.41	29.48	34.63	28.98	32.26	32.08	36.63
An	23.76	19.35	21.24	22.34	15.53	15.66	0.85
Ne	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Di	7.26	15.73	6.23	7.58	9.01	8.86	0.0
Hy	15.18	10.99	11.93	17.83	10.57	10.26	0.93
Ol	2.17	0.0	2.63	0.0	0.0	0.0	0.0
Mt	4.11	3.55	3.86	3.46	2.77	2.69	0.32
Il	4.27	4.02	4.56	3.52	2.87	2.85	0.46
Ap	2.20	1.03	1.86	1.19	0.86	0.71	0.07
Py	0.15	0.58	0.13	0.55	0.45	0.09	0.21
Cor	0.0	0.0	0.0	0.0	0.0	0.0	0.52

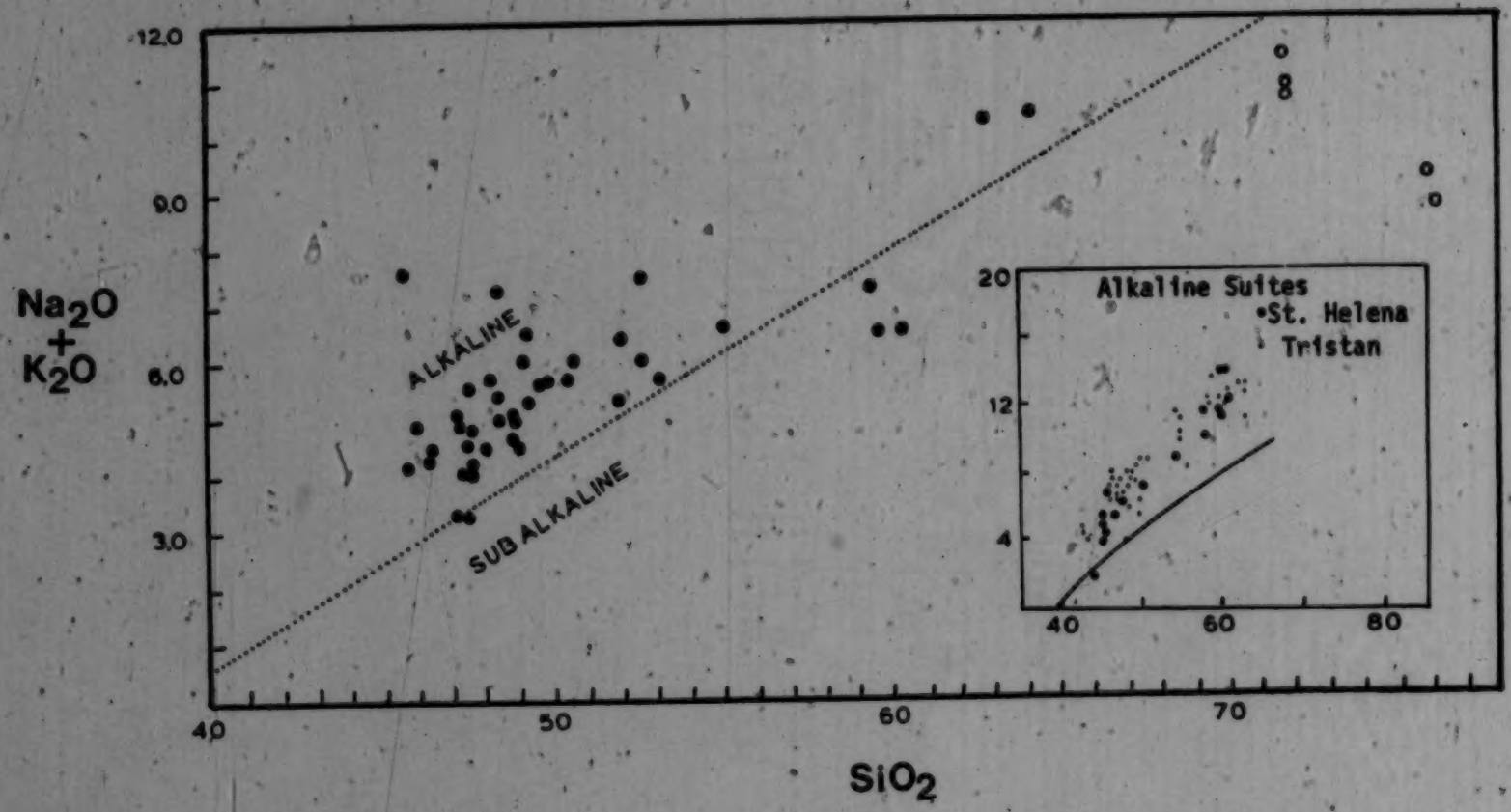

Fig. 7. Silica vs. alkalis diagram, Heart Peaks volcanics. Boundary after MacDonald and Katsura (1964). o Heart Peaks Formation. • Level Mountain Group.

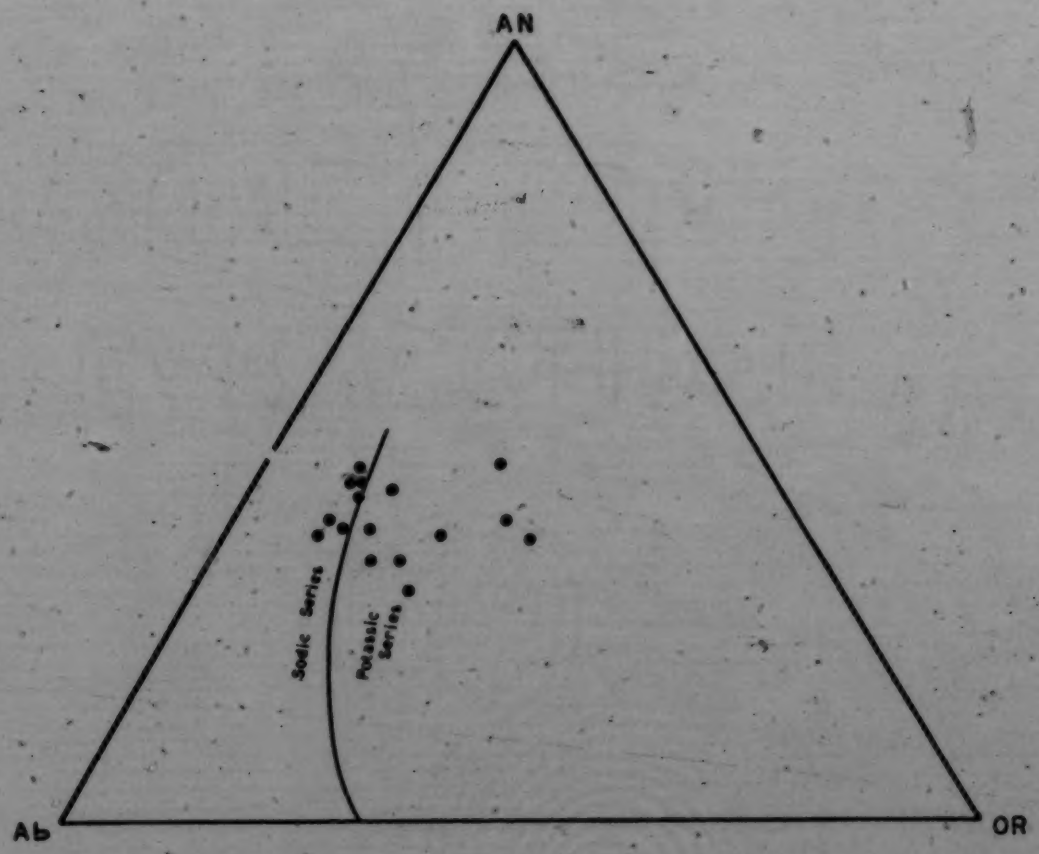

Fig. 8 Plot of rock compositions in terms of normative An - Ab - Or.

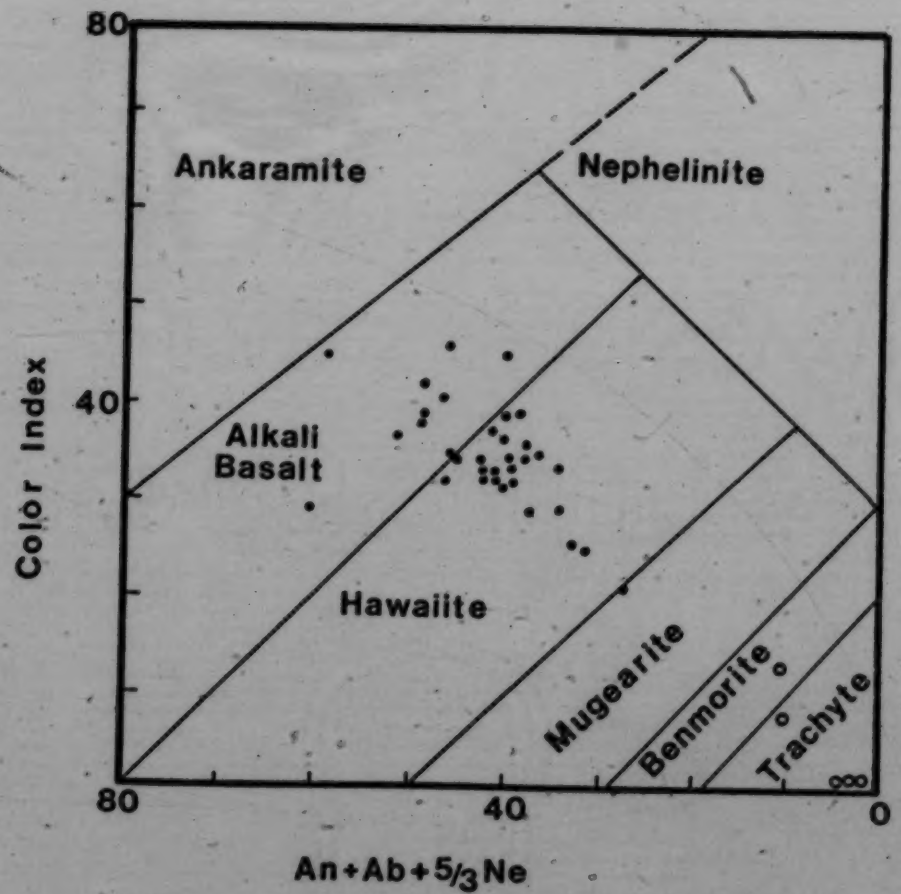

Fig. 9.-Classification of Heart Peaks volcanics. Boundaries after Irvine and Baragar (1971). ○ Heart Peaks Formation ● Level Mountain Group

felsic nature of the rocks of the Heart Peaks Formation.

Adjustment of chemical analyses for ferrous and ferric iron ratios is necessary when microprobe and XRF analyses are reported as only total iron is analysed. The method adopted here is to set $Fe^{+++}/(Fe^{++} + Fe^{+++}) = 22.3$ atomic percent.

The occurrence of variable amounts of hornblende both as a groundmass phase and as phenocrysts in intermediate and mafic rocks complicates, in some cases, the comparison of modes and norms. Hornblende will not be indicated in the norm, but its presence will affect the kf and hyp norm components. The occurrence of modal hornblende will tend to increase the normative hyp component. The appearance of normative quartz in intermediate rocks of the Level Mountain Group and all rocks of the Heart Peaks Formation is in agreement with the modal analyses.

Major Element Variation

Figures 10 and 11 show the variation of major elements against silica. Alkali basalts as characterized by enrichment in total iron, CaO, TiO_2, MgO, and P_2O_5. Table III compares absolute abundances of Heart Peaks basalt average with other alkali basalt compositions. Transitional and mildly alkaline basalt from the Baikal Rift area show the closest overall similarities. The high TiO_2 content appears to be distinctive to Heart Peaks rocks. Hawaiites and trachybasalt show progressive depletion in total iron, CaO, TiO_2, MgO and P_2O_5 and

S

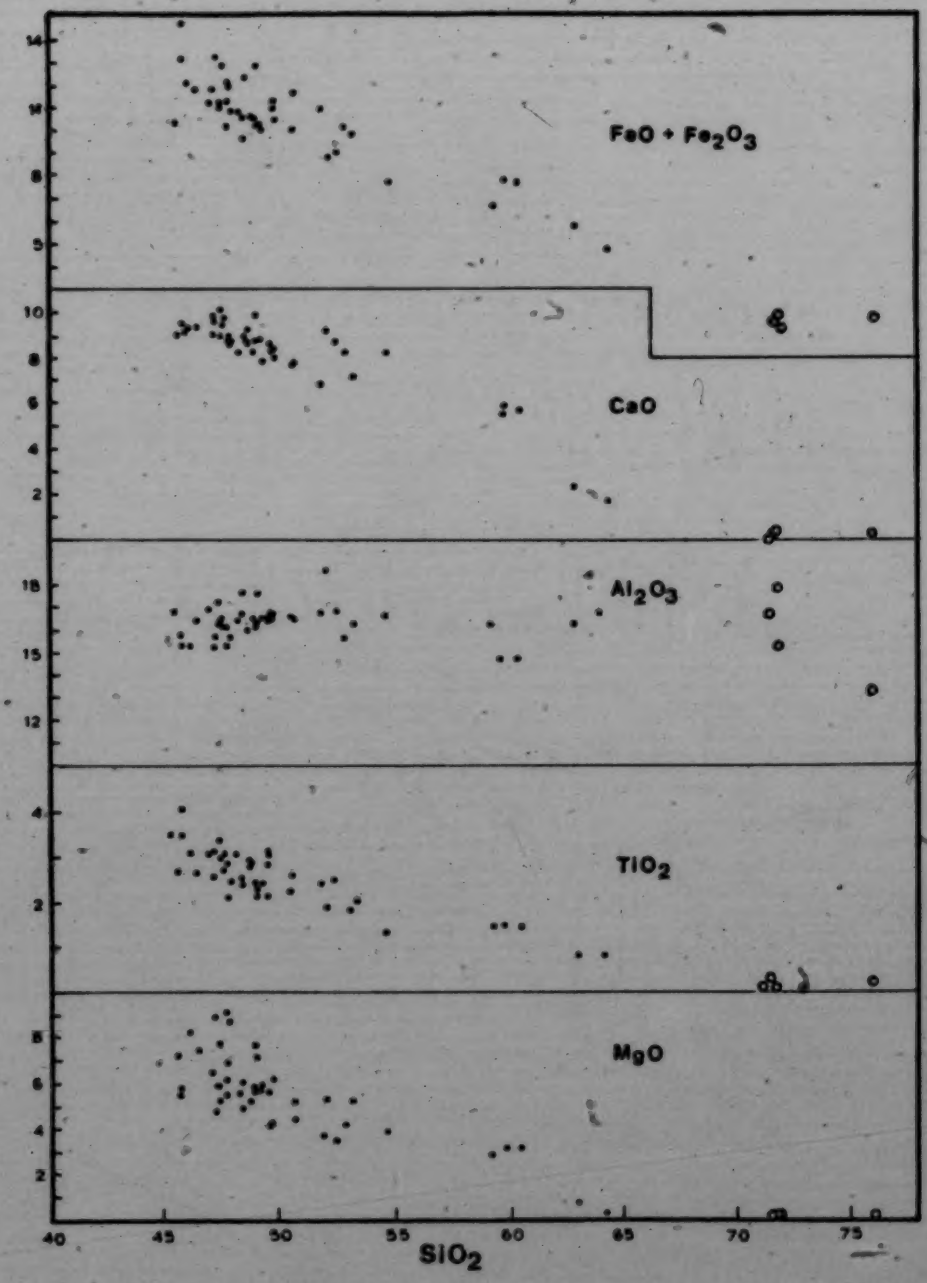

Fig. 10. Major element variation diagrams, Heart Peaks volcanics.
- Level Mountain Group
- Heart Peaks Formation

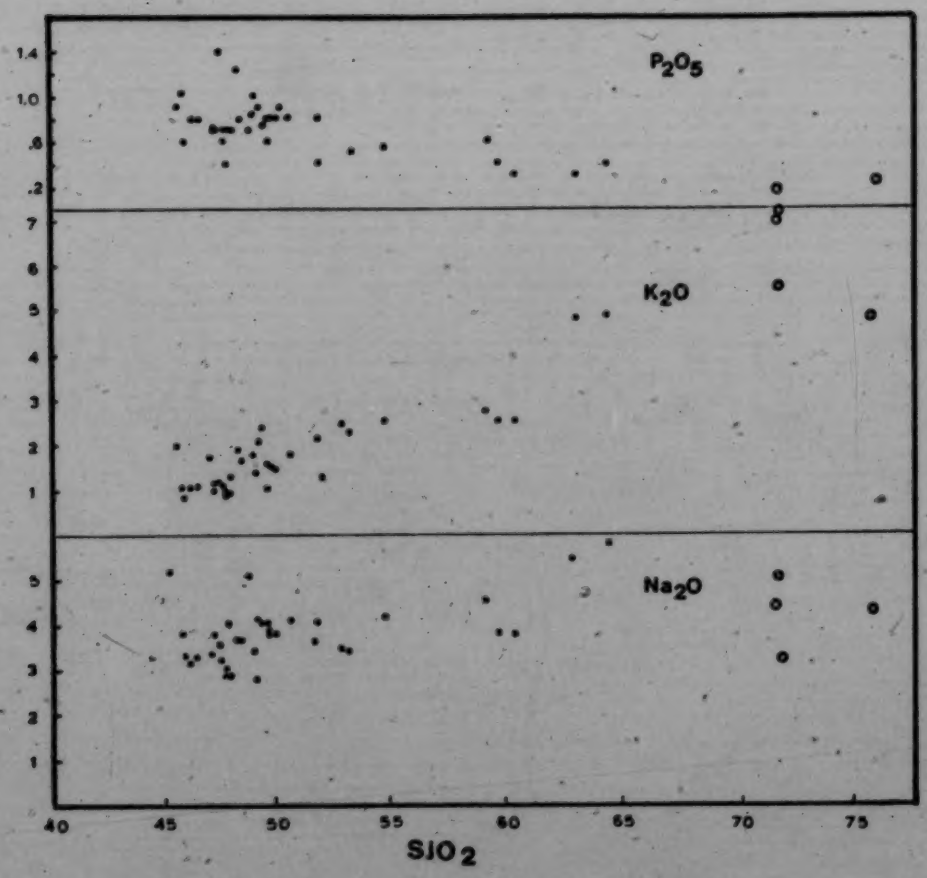

Fig. 11. Major element variation diagrams, Heart Peaks volcanics.
- Level Mountain Group
- Heart Peaks Formation

TABLE III

AVERAGE BASALT COMPOSITIONS

	Heart Peaks Alkaline Basalt (7)	St. Dev.	Basin and Range Transitional Basalt (36)	Baikal Transitional (7)	Baikal Mildly Alkaline (8)	Gregory Rift, Kenya Basalt (5)
SiO_2	46.23	1.26	48.50	46.67	46.93	48.04
Al_2O_3	15.76	0.88	15.10	14.72	16.28	15.10
TiO_2	3.19	0.28	1.77	2.84	2.11	2.02
Fe_2O_3	2.82	0.37	2.90	2.34	4.76	2.98
FeO	8.84	1.16	6.90	9.89	7.20	8.92
MgO	7.96	1.3	7.45	8.30	7.84	6.35
CaO	9.41	0.69	9.50	8.37	8.34	12.60
Na_2O	3.53	0.46	3.52	3.94	3.51	2.69
K_2O	1.54	0.50	1.48	1.97	1.69	0.78
P_2O_5	0.92	0.23	0.50	0.36	0.36	0.31
MnO	0.15	0.03	0.15	0.15	0.26	0.20
Total	100.35		99.77	99.55	99.28	99.99

Baikal - Kiselev et al. (1978)
Basin & Range - Leeman and Rogers (1970)
Gregory Rift - Baker et al. (1977)

AVERAGE BASALT COMPOSITIONS

NORMS

	Heart Peaks Alkaline Basalt	Basin and Range Transitional Basalt	Baikal Transitional Mildly Alkaline		Gregory Rift, Kenya Basalt
Q	0.0	0.0	0.0	0.0	0.0
or	9.07	8.95	11.71	10.00	4.61
ab	21.55	27.31	17.80	24.40	22.08
an	22.53	21.51	16.73	23.70	26.83
ne	4.45	1.71	8.50	2.90	0.37
di	14.53	18.80	18.37	12.30	27.51
hy	0.0	0.0	0.0	0.0	0.0
ol	15.53	13.78	17.21	14.20	9.70
mt	4.07	4.30	3.41	6.90	4.32
il	6.04	3.44	5.42	4.00	3.84
ap	2.13	1.19	0.84	0.80	0.72

enrichment of K_2O. TiO_2, CaO and K_2O show the best correlation with silica. Considerable scatter in Na_2O values may be due to factors such as losses during alteration and during analysis by the electron beam.

The lack of compositions in the silica range 50-54% is indicative of silica gaps seen in many alkali rock series. These "Daly" gaps have been suggested to be incompatible with a derivation of the liquids by fractional crystallization (MacDonald et al., 1970; Chayes, 1963). Acidic compositions are scarce mainly because of difficulties in getting representative unaltered samples. This contributes to uncertainties regarding the link between the Level Mountain Group and the Heart Peaks Formation. Smooth major element trends in Level Mountain Group lavas, particularly with TiO_2, CaO and K_2O support a fractional crystallization model where mugearite, trachybasalt and hawaiite are derived from parental alkali olivine basalt. Variation of MgO and $FeO + Fe_2O_3$ values may be partly due to settling of early formed olivine crystals.

Figure 12 shows the AFM trend of Heart Peaks volcanics in relation to alkaline trends at Hawaii, the Hebrides, Tristan da Cunha, and a typical tholeiitic trend. The Level Mountain Group rocks plot in a range similar to fractionation trends seen in other alkalic centres, with less iron enrichment than typical tholeiitic trends. The lack of a single clearly defined fractionation trend may indicate variation of oxygen pressure during fractionation. High oxygen pressure would

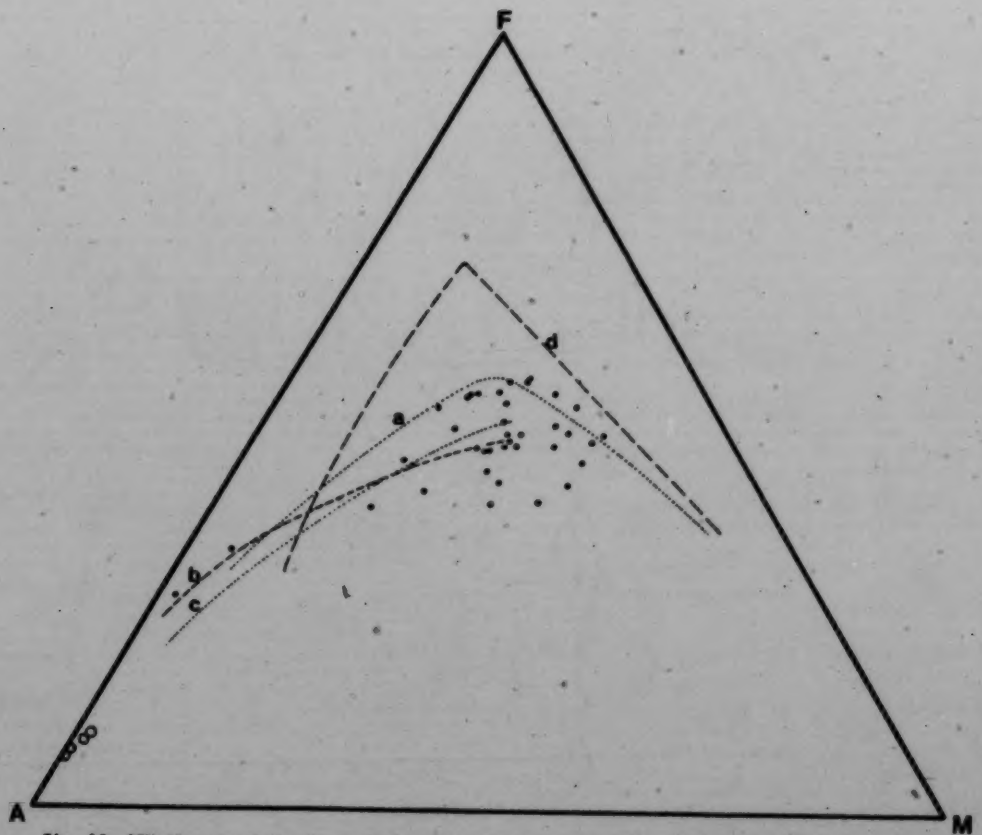

Fig. 12. AFM diagram of the Heart Peaks volcanics. a - Hawaiian trend, b- Calc-Alkaline trend, c - Tristan da Cunha, d - Skaergaard. o Heart Peaks Formation • Level Mountain Group

cause iron oxides to crystallize, causing iron depletion, while low oxygen pressures would favor iron enrichment. It has been suggested that this mechanism has affected fractionation trends in alkaline volcanics of the Assab Range of Ethiopia (De Fino et al., 1973).

Trace Elements

Trace and major elements have been analysed in 15 rocks by X-ray fluorescence methods.

Trace element abundances and variation are now commonly being used as indicators of magma series, tectonic setting, and petrogenetic processes (Pearce and Cann, 1973; Floyd and Winchester, 1975; Gast, 1968). Winchester and Floyd (1977) have used immobile elements to classify differentiation products of alkaline and subalkaline magma series using a series of variation diagrams. Immobile element concentrations (Nb, Zr, Y) from known volcanic environments have been found to show distinct enrichment patterns related to the alkalinity of the magma. Figure 13 illustrates that Nb/Y ratios of Level Mountain Group rocks are high, characteristic of alkaline rock suites. The silica content is used as an indicator of differentiation. Two samples from the Heart Peaks Formation plot in the strongly alkaline range, which are inconsistent with major element indicators. Figure 13 also indicates the relative constancy of inter-element ratios of the immobile elements.

Barium, strontium, and rubidium are principally controlled by feldspar crystallization. If K_2O is used as an indicator of differentiation, Sr and Ba can be seen to be enriched in liquids to a point

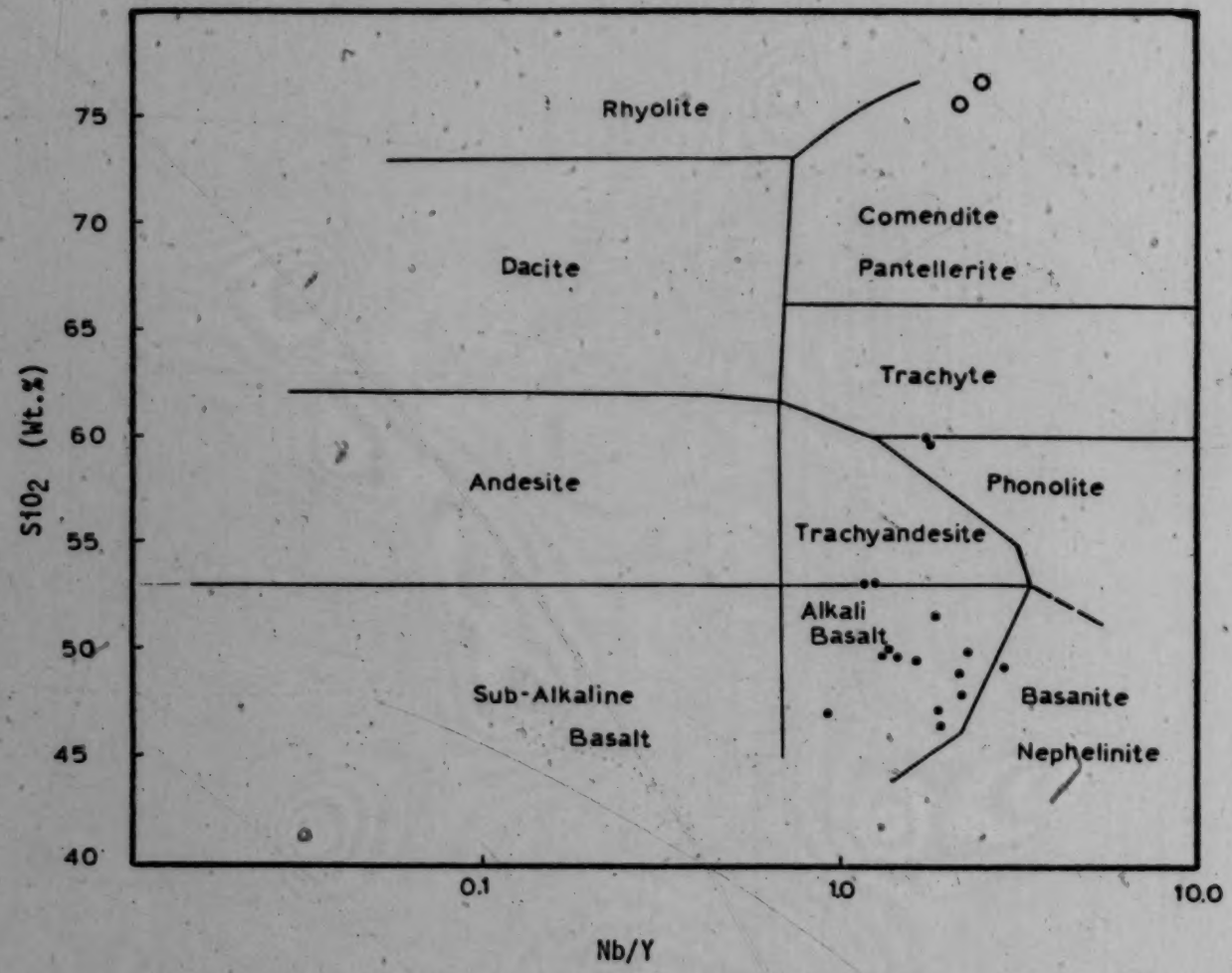

Fig. 13. Classification of volcanics using immobile elements.
o Heart Peaks Formation • Level Mountain Group
Boundaries after Winchester and Floyd (1977).

where they both begin to be depleted by crystallization of plagioclase and alkali feldspar respectively. Rubidium is continually enriched in the residual liquids. Zirconium shows initial enrichment in basaltic rocks. Rb/Sr ratios are similar to those typical of alkaline basalts. Chromium shows a wide variation in rocks of comparable K_2O contents as does Ni, but in general K_2O rich rocks are strongly depleted in these elements which would be removed in early phases such as olivine and pyroxene: see Figure 14.

These trace element patterns are similar to those of alkaline magma series of the oceanic islands, of which St. Helena is particularly representative.

Strontium and Oxygen Isotopes

Oxygen isotope studies can be important in the study of volcanic rocks with regards to the role of fractional crystallization, contamination by assimilation of country rocks, genetic relationships between magmas and secondary hydrothermal and deuteric effects (Taylor, 1968).

In a magmatic environment, fractionation of oxygen isotopes between crystals and melt will be small because of the typically high temperatures involved (800-1200°C). Nevertheless, oxygen isotope fractionations can have meaningful values in this temperature range for the process of fractional crystallization as has been shown by Matsuhisa (1973).

An important observation on primary, uncontaminated basaltic

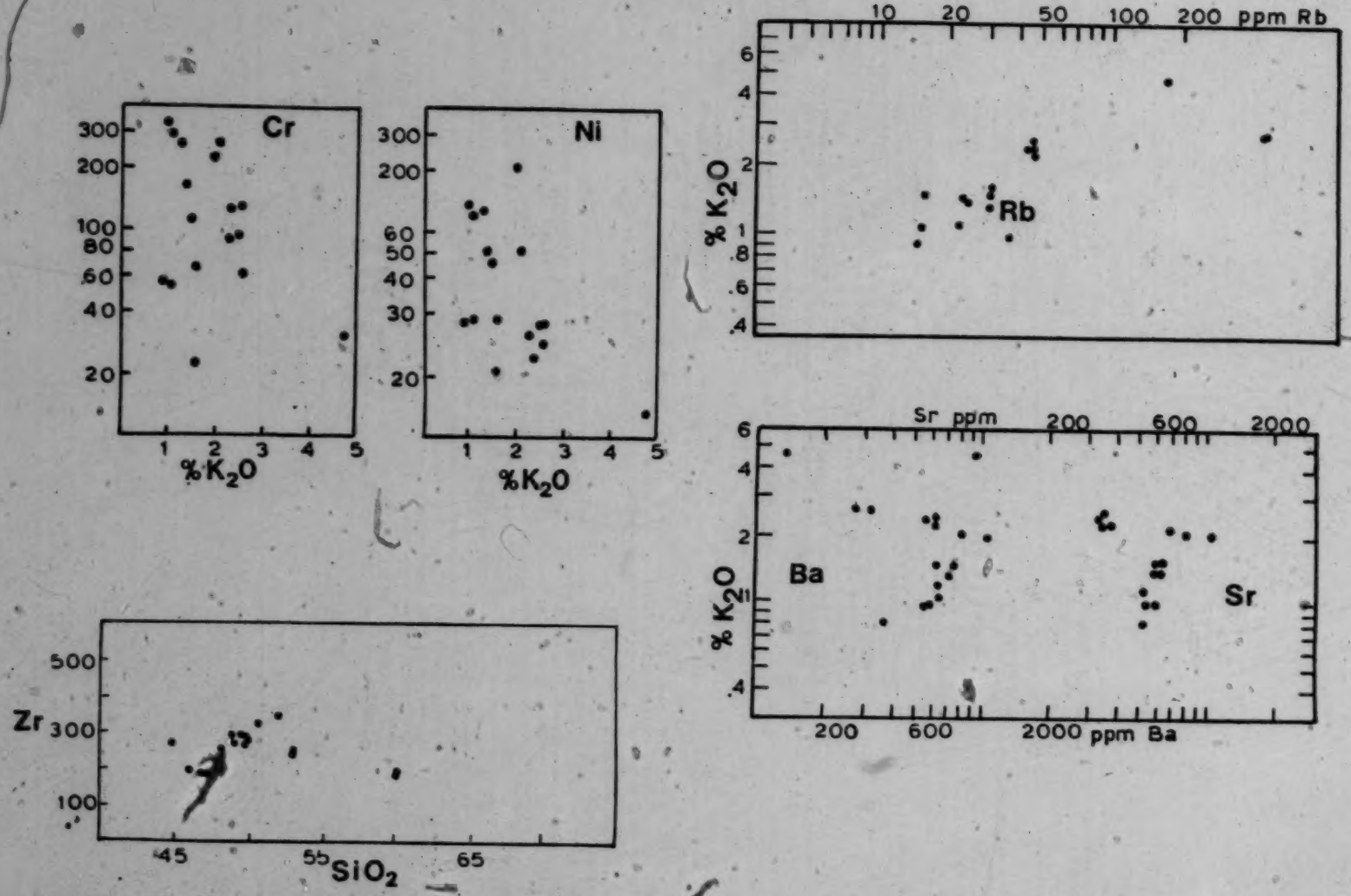

Fig. 14 . Trace element variation in Level Mountain Group rocks.

rocks is that material which is thought to have been derived from the mantle typically shows a δO^{18} value of 5.9‰ (Taylor, 1968). Continental crust, on the other hand has a wide range of values (7.8 - 10.2‰ for granitic rocks).

The aim of an oxygen isotope study touches on three aspects of the Heart Peaks volcanics:

1) The relationship between acid and basic eruptives with respect to fractional crystallization or contamination processes;

2) The relationship between hornblende inclusions and their host basaltic rocks;

3) The role of H_2O in the magmatic environment.

Oxygen isotope measurements on representative rock types and minerals from Heart Peaks rocks are presented in Table IV. In cases where the fine grained groundmass of specimens showed obvious signs of secondary alteration, mineral separates were obtained to obtain a representative primary analysis. For example, the analysed $^{18}O/^{16}O$ ratio of sanidine from sample TOC should closely approximate the whole rock value because sanidine, with minor quartz, is the major constituent of the rock and the fractionation factor between sanidine and melt is similar to that of quartz (the only other significant constituent).

The δO^{18} values for alkali-basalt (5.44‰) and andesite (6.47‰) fall within the low range typical of unaltered primary basalt. Figure 15 shows the oxygen isotoperdata of the Heart Peaks rocks compared with

TABLE IV

STRONTIUM AND OXYGEN ISOTOPE ANALYSES;

HEART PEAKS VOLCANICS

Sample No.	Location and Description		δO^{18} ‰(SMOW)
JC 1	Inclusion in Hawaiite flow Level Mountain Group	Hornblende	4.89
0788-12	Alkali basalt flow; Level Mountain Group	Pyroxene	5.44
4261-19	Alkali basalt flow; Level Mountain Group	Whole Rock	5.66
7788-13A	Andesite flow; Level Mountain Group	Whole Rock	6.47
TOC	Rhyolite from Heart Peaks Formation	Sanidine	8.63
			$87Sr/86Sr$
4261-22	Alkali basalt flow; Level Mountain Group		.70344 ± .00002 (393.18 ppm Sr)
TOC	Rhyolite from Heart Peaks Formation	Whole Rock	.71155 ± .00027 (21.06 ppm Sr)
NBS 987	Standard: Official value		.71014
	Measured Value		.71006 ± .00010

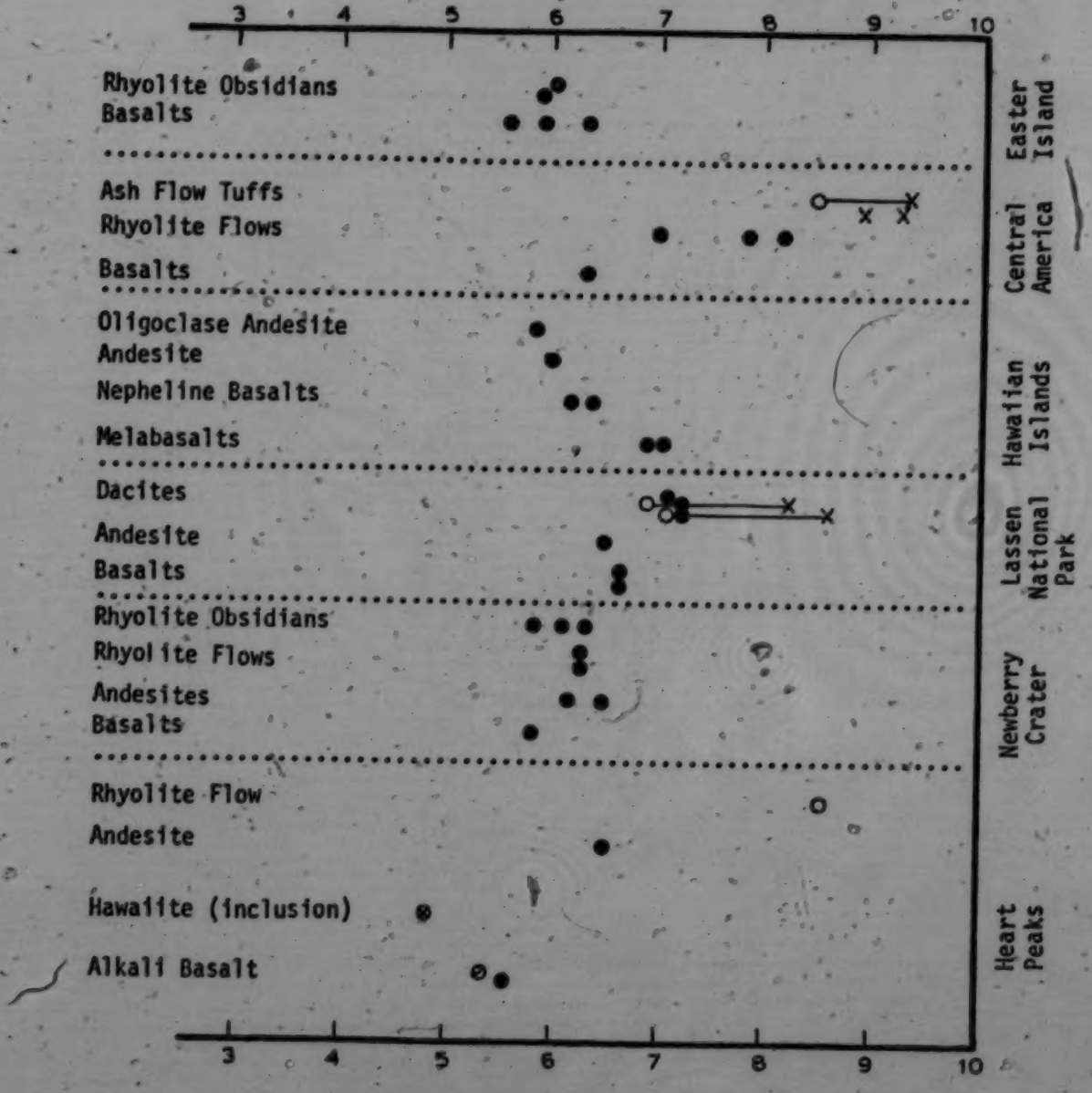

Fig. 15. Graph showing variation of $^{18}O/^{16}O$ in several volcanic centres compared to Heart Peaks centre. ○ Feldspar. × quartz. ⊗ hornblende. ⊘ pyroxene. ● whole-rock. Other data from Taylor(1968).

data from numerous other volcanic centres. The values for average age ultramafic rocks are similar to the basalt range which may indicate a common upper mantle source region for the basalt and ultramafic rocks (Taylor, 1968).

The spread in δO^{18} values from 5.6‰ in alkali basalt through 6.47‰ in andesite to 8.63‰ in rhyolite appears to show a rough correlation between silica content and O^{18}/O^{16} ratios. The effects of fractional crystallization on the values of comagmatic rock suites has been demonstrated by Matsuhisa (1973) for several rock suites in Japan. Where a correlation can be found between solidification index (as an indicator of fractional crystallization) and δO^{18} values, the δ values from the most basic to most acidic rocks differ in the order of 1‰. In these cases it has been assumed that there is a homogenous source of δO^{18} depleted basaltic material and equilibrium fractionation is maintained between liquid and crystals. Taylor's data show that $^{18}O/^{16}O$ ratios of basalt and rhyolite from oceanic islands all show similar values, with the late differentiates being either slightly enriched or slightly depleted with respect to parental basaltic magmas. In the alkaline rock series of Japan, the correlation between solidification index and δO^{18} breaks down for the silica rich alkaline rhyolites and trachyte, while tholeiitic and calc-alkaline differentiation series show good correlation throughout the sequence. In the Level Mountain Range (Hamilton and Muehlenbachs, 1977) a complex pattern of δO^{18} values has been found where peralkaline acid rocks have a wide range from 5.6‰ to 10.0‰ in contrast to homo-

genous values (5.7-6.5‰) for basaltic rocks (Hamilton and Muehlenbachs, 1977). The breakdown of correlation of δO^{18} values between basic and acid rocks in these cases has been suggested to indicate that the acid rocks are not related to basic rocks by simple differentiation mechanisms.

In the light of these examples, it appears that the spread of oxygen isotopic values between basalt and rhyolite at Heart Peaks (2.9‰) may be too high to be accounted for by fractional crystallization models. Related to this problem, Taylor (1968) has proposed several factors which may be responsible for high $^{18}O/^{16}O$ values in volcanic rocks:

1) Crustal assimilation of ^{18}O rich country rocks;

2) Crystallization and equilibration of acidic magmas in a high P_{H_2O} environment where crystallization of hornblende or biotite is possible;

3) Fundamental differences in the nature of the parent material.

Rocks enriched in ^{18}O are most available in areas of continental volcanism and are likely to have contaminated volcanics causing high $^{18}O/^{16}O$ ratios. This mechanism is suggested by Taylor (1968) to be responsible for the high $^{18}O/^{16}O$ ratios in obsidians from the continental U.S.A. compared to oceanic obsidians. The occurrence of crust derived inclusions in rocks of the Heart Peaks Formation indicates the contamination by assimilation of these rocks may have occurred but its extent is difficult to assess.

Kaersutitic hornblende appears to have been freely crystallized

in intermediate rocks (Sample 7788-13). Since hornblende is lower in ^{18}O than any of the common igneous minerals except magnetite, its crystallization in significant amounts in an environment of high P_{H_2O} would have the effect of enriching the residual liquids in ^{18}O. δO^{18} value of kaersutite inclusions in basalt is 4.89‰. The occurrence of this mineral indicates high P_{H_2O} conditions under magmatic conditions. This mechanism is suggested by Taylor to account for high ^{18}O ratios in certain acid volcanic rocks of the continental U.S.A.

Strontium isotopic measurements on basalt from the Level Mountain Group and rhyolite from the Heart Peaks Formation give values of $^{87}Sr/^{86}Sr$ = 0.70344 and 0.71155 respectively. The low value for basalt is typical of strontium isotopic composition of mantle derived rocks. Basaltic rocks in the Level Mountain Range have very low $^{87}Sr/^{86}Sr$ ratios in the range .7025-.7044 (Hamilton, et al., 1978). The isotopic ratio of rhyolite (.71155) however, appears to be anomalous. This ratio could be generated from an initial ratio of about .7034 only over a period in the order of sixty million years. This would indicate a much older age for the Heart Peaks Formation than other evidence indicates, thus other possibilities must be considered to account for this strontium isotopic ratio. The most likely mechanisms include contamination by assimilation of ^{87}Sr-enriched crustal rocks (Powell and Bell, 1974) or secondary alteration processes involving strontium exchange. Data available at present are not sufficient to verify any of these mechanisms which may cause high $^{87}Sr/^{86}Sr$ ratios in rhyolite.

CHAPTER VII

MINERALOGY

Appendix C contains electron microprobe analyses of principle minerals found in lavas of the Level Mountain Group and the Heart Peaks Formation. Sources of error in microprobe analyses of thin sections are numerous and may not always be quantitatively determined. Common sources of error include:

1) Operator error: slight defocussing of electron beam or positioning the electron beam too close to grain boundaries.

2) Incorporation of minute inclusions in the analysis.

3) Systematic errors in counting statiatics.

4) Inhomogeneities due to exsolution or zoning in crystals.

5) Instability of volatile elements under the electron beam (particularly Na, K and P).

Any analyses with totals less than 98% or greater than 102% have been neglected.

Feldspar

Feldspar, the most abundant crystalline phase in the Heart Peaks volcanics shows a variety of compositions and morphologies. In the most mafic rocks plagioclase exists only as a minor groundmass phase which shows variation in composition from An_{49} to An_{59}. Rare grains of alkali feldspar are found in the groundmass but are generally too small to be analysed.

In medium grained subophitic basalts, euhedral plagioclase crystals show strong zoning varying from An_{59} to An_{68} in individual grains. Alkali feldspar is also present in minor quantities.

Fine grained hawaiites often contain large euhedral feldspar crystals which are crowded with pyroxene and opaque oxide inclusions. The phenocrysts have relatively sodic rich compositions (An_{42}) compared to calcium rich groundmass feldspar (An_{63}). It is evident that these crystals do not represent an equilibrium assemblage with groundmass feldspars. Sodic phenocrysts may have crystallized from a magma of different composition and were mixed into the more calcium rich liquid in which they are found. Other phenocrysts in hawaiites are clear, free of inclusions, and partly enveloped by groundmass titaniferous pyroxene. These phenocrysts (An_{58} to An_{61}) appear to be close to being an equilibrium assemblage with groundmass crystals.

Broken and angular phenocrysts sometimes show two distinct stages of growth; an unzoned core (An_{54}) and a zoned rim (An_{59}) separated by a fine line of opaque inclusions.

These morphologies suggest a complex pre-eruptive history during which feldspars have been crystallized and mixed into different liquid compositions, where crystallization has continued.

Rocks of intermediate composition (7788-13) also show evidence of mixed feldspar compositions. Groundmass sanidine ($An_9 Ab_{58.5} Or_{32.5}$) coexists with andesine (An_{37}) and labradorite microphenocrysts (An_{62}). The labradorite is not likely to have crystallized in equilibrium with the

groundmass. The composition of coexisting andesine and sanidine may be used as a geothermometer. The curves of Stormer (1975) are based on the albite content of coexisting feldspars. It is reasonable to assume, since the feldspars are groundmass phases, that crystallization took place at low pressure. The albite component of the coexisting feldspars indicate crystallization at approximately 870°C for hornblende bearing andesite.

Trachyte from the Heart Peaks Formation (7788-8) contains feldspars of widely varying compositions. Labradorite (An_{51}) is mantled by sanidine (An_{10} Ab_{27} Or_{63}) in phenocrysts which occur as irregular aggregates and are often crowded with opaque inclusions and alteration. Groundmass orthoclase has the composition $An_{10}Ab_{27}$ Or_{63} and show patches of exsolved albite rich feldspar (An_{6} Ab_{57} Or_{37}). Labradorite phenocrysts may be an equilibrium assemblage as plagioclase of this composition (An_{50} - An_{60}) is often found with alkali feldspar in trachytes (Rahman and MacKenzie, 1969). Sanidine from rhyolite and other quartz-rich trachytes is similar in composition to sanidine in trachyte but generally there is no coexisting plagioclase.

The composition of feldspars is plotted on the ternary An-Ab-Or diagram (Figure 16). Though individual rocks show crystals with reverse and complex zoning due to mixing of phenocrysts, these analyses represent a fractionation trend where Ca-rich plagioclase crystallized first followed by more sodic compositions which crystallized

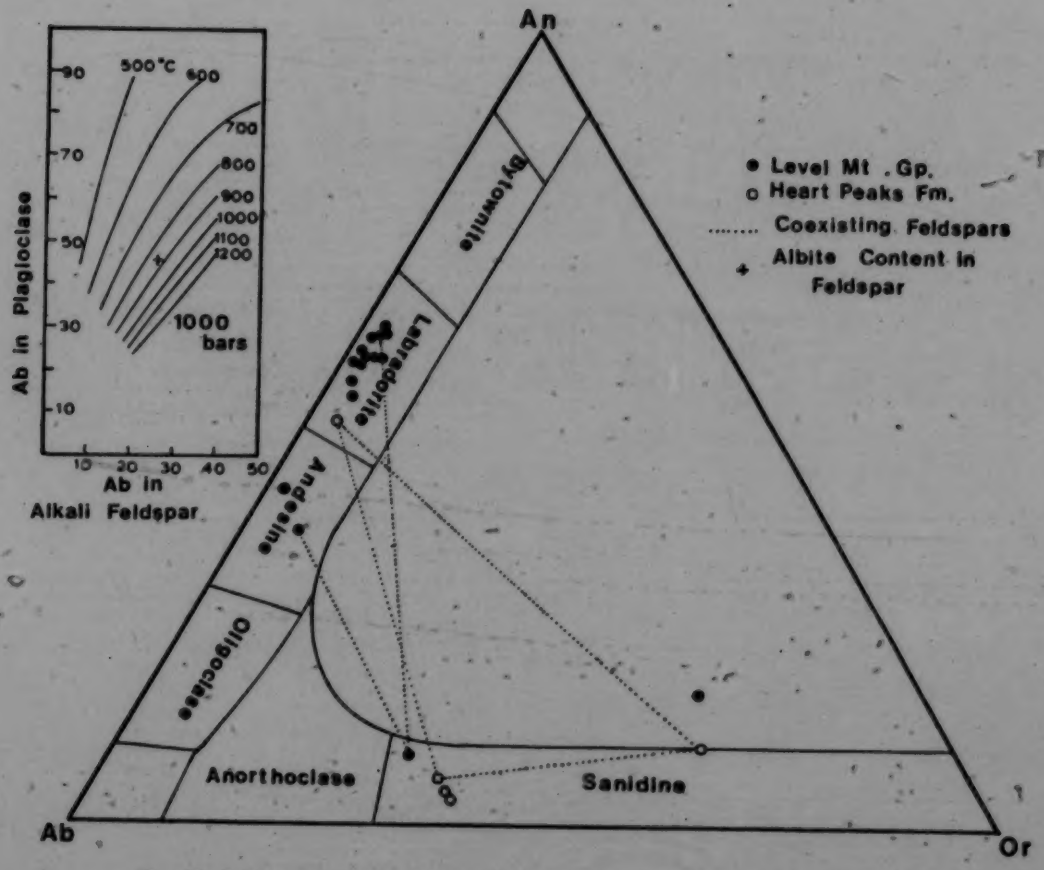

Fig. 16. Feldspar compositions in Heart Peaks volcanics and feldspar geothermometer after Stormer (1975).

simultaneously with alkali feldspar.

Pyroxene

Pyroxene of alkali olivine basalt magma is typically a single Ca-rich clinopyroxene. Orthopyroxene or Na rich pyroxenes have not been found in Heart Peaks lavas. Clinopyroxene composition from Level Mountain Group rocks are found in Appendix B.

Pyroxene from alkali-olivine basalts are rich in TiO_2 and Al_2O_3. Kushiro (1960) and Verhoogen (1962) have indicated the silica activity directly affects aluminum and titanium activity in pyroxenes. Liquids of low silica activity where feldspar is stable favor the incorporation of Al in both Z and XY sites in pyroxene. Table V shows compositions of Ca-rich pyroxenes in lavas of varying silica activity compared to alumina-rich pyroxene from hawaiite and alkali-olivine basalt of the Level Mountain Group. The alumina content of alkali basalt indicates conditions of very low silica activity, comparable to that in strongly undersaturated lavas. A high percentage of alumina is thus allowed in both Z and XY sites.

Figure 17 shows pyroxene compositions in terms of the Mg, Ca and Fe components. Fractionation trends have a limited range, typical of pyroxene from alkali basalt lavas, and show uniform Ca enrichment.

Olivine

Olivine coexisting with Ca rich plagioclase and Ca, Al-rich clinopyroxene has a composition of Fo_{85} Fa_{15}. Olivine compositions range to Fo_{55} Fa_{45} in trachybasalt. Olivine is not as important as

TABLE V

COMPOSITIONS OF Ca-RICH PYROXENE IN LAVAS OF VARYING SILICA ACTIVITY (From Carmichael et al. 1974) COMPARED WITH PYROXENE FROM LEVEL MOUNTAIN GROUP LAVAS

	Olivine Tholeiite	Leucite Basanite	Leucite Phonolite	Hawaiite LMG	Alkali Basalt LMG
SiO_2	52.4	46.6	40.3	50.31	46.16
TiO_2	0.97	1.60	2.43	2.46	2.57
Al_2O_3	1.77	8.60	11.3	2.46	8.80
FeO	9.80	7.90	16.6	13.09	6.97
MnO	0.19	0.22	0.56	0.23	-
MgO	16.20	12.0	5.30	10.89	13.00
CaO	18.40	22.8	23.0	20.83	20.92
Na_2O	0.32	0.29	0.54	.73	.89
Total	100.05	100.01	100.03	101.00	99.31
Z Si	1.942	1.746	1.594	1.90	1.72
Al^{IV}	.058	.254	.406	.10	.28
Al^{VI}	.019	.126	.121	.01	.10
Ti	.027	.045	.072	.04	.07
XY Fe	.304	.247	.549	.41	.27
Mn	.006	.007	.018	.61	.006
Mg	.895	.667	.312	.008	.73
Ca	.731	.915	.975	.84	.84
Na	.023	.021	.041	.05	.06
% Al in Z	2.9	12.7	20.3	5.0	14.0

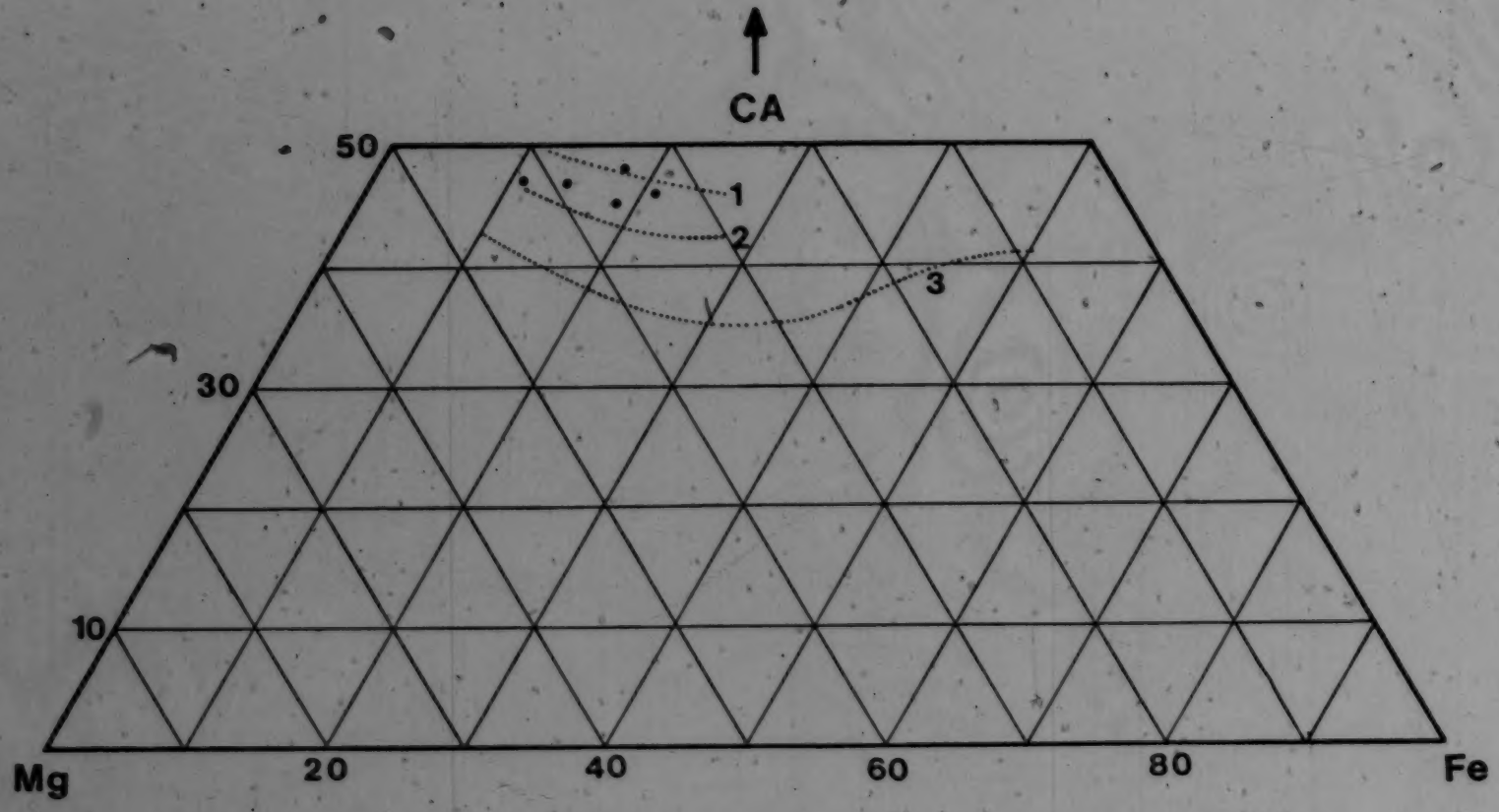

Fig. 17. Pyroxene compositions in Heart Peaks volcanics. Trend 1 - Black Jack Sill, Trend 2 - Garbh Eilean Sill, Trend 3 - Skaergaard. • Level Mountain Group.

pyroxene as a phenocryst phase in the most mafic rocks. It is generally restricted to the groundmass.

Opaque Oxides

Opaque oxides are a ubiquitous phase in all rocks of the Heart Peaks volcanics. Characteristic of most alkali basalts, the rocks at Heart Peaks lack ilmenite. In liquids of low silica activity, the formation of titaniferous pyroxene occurs at the expense of ilmenite, thus titanomagnetite usually forms the only oxide phase. The absence of two coexisting oxides prevents the use of the Fe-Ti oxide geothermometer.

Alkali basalt has been found to contain corroded fragments of aluminous spinel. The composition of these rare fragments fits in the spinel-hercynite solid solution (Mg, Fe) Al_2O_4. The fragments are rimmed with titanomagnetite, which is the common groundmass phase. Haggerty (1976) illustrates that spinels of this composition are typical of those found as xenoliths in basalts, kimberlites and alpine-type peridotites (Figure 18). They may represent a very early, high pressure crystallizing phase. The titanomagnetite rim indicates that crystallization was completed in lower pressure conditions.

Amphibole

Titanium-rich amphibole of the pargasite-hastingsite series (kaersutite) occurs as inclusions in intermediate and basaltic flows, a primary phase of gabbroic inclusions, and as a groundmass phase in intermediate lavas. Amphibole composition generally cannot be correlated with magma compositions, and kaersutite in particular has been

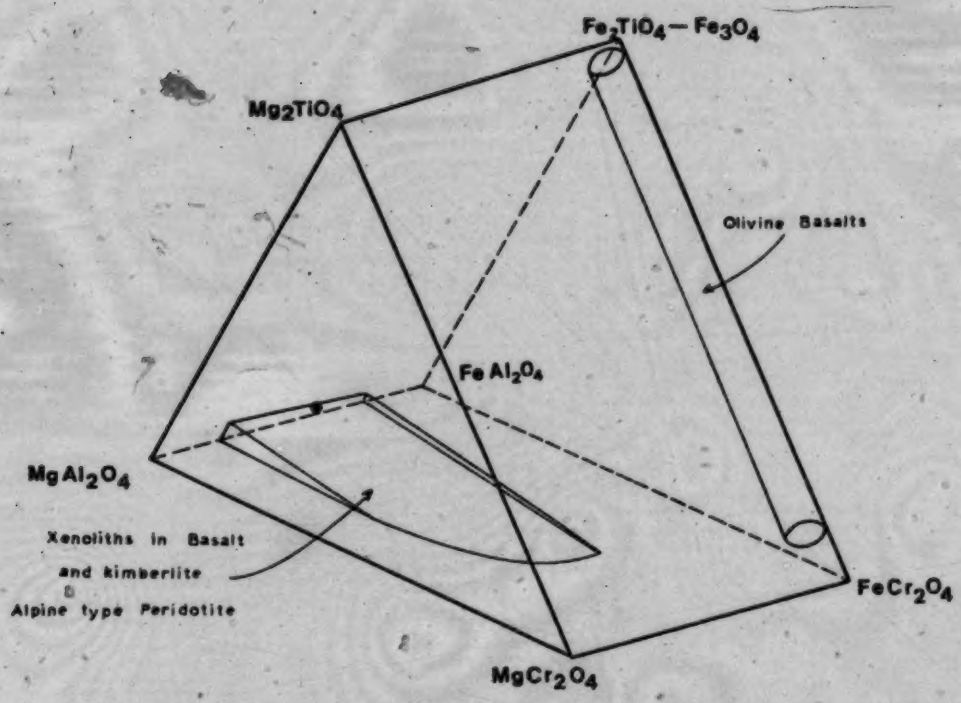

Fig. 18. Composition and occurrence of spinel in volcanics. Solid circle indicates composition of spinel in sample 4261-19. (Haggerty, 1976).

known to occur in a wide range of magma types (Carmichael et al., 1974). The composition of kaersutite nodules found in Level Mountain Group basalt is similar to nepheline normative alkali basalt. The abundance and distribution of kaersutite inclusions in Level Mountain Group rocks indicates conditions of high P_{H_2O} which are necessary for the crystallization of a hydrous mineral. This phase may have crystallized freely at some stage and may have caused contamination of some lavas by sinking and resorption. Early crystallization and resorption of hornblende has been suggested to result in the increase in the mafic component of intermediate and felsic lavas and allow an undersaturated condition to continue in the magma (Bowen, 1928; Benson, 1939). In this case, if hornblende had crystallized from intermediate lavas, the remaining liquid would tend to become oversaturated. Since these mechanisms are very difficult to evaluate it should be noted that the importance of hornblende crystallization is as an indicator of P_{H_2O} conditions in the intermediate magma compositions.

CHAPTER VIII

PETROGENESIS

Partial fusion and fractional crystallization are the most relevant mechanisms thought to be responsible for the origin and diversity of magmatic liquids. The fact that some degree of partial fusion of appropriate parental material must be responsible for initial magma generation is accepted, however the extent to which partial fusion, as opposed to fractional crystallization, controls the variation of erupted magma compositions must be considered. Yoder (1973) and Chayes (1977) suggest that the mechanism of partial fusion may be applicable to the production of contemporaneous magmas of widely varying compositions without a continuum of intermediate liquids. Despite the dispute over the existence of 'Daly' gaps (Baker, 1968) the mechanism of partial fusion has been attracted to suites of alkaline volcanics which often appear to show a distinct bimodal distribution of magma compositions. Presnall (1969) and Yoder (1973) have presented model for partial melting behaviour which might generate trachytic and basaltic liquids from a quartz normative parent and suggest that this mechanism may be applicable to undersaturated parental rocks.

Some advocates of fractional crystallization models for alkaline rock suites have questioned the existence of 'Daly' gaps (Baker, 1968; Cann, 1968). Baker et al., (1977) attribute the apparent bimodal frequency of basic and felsic compositions to the efficiency of a basaltic

parent to produce trachyte. The trachytic liquids, which have formed in intracrustal magma chambers, are preferentially erupted due to their relatively low specific gravity. Mass balance equations for major element compositions and Rayleigh law modelling of trace element contents support fractional crystallization as the dominant mechanism in the East African Rift lavas (Baker et al., 1977) and in the Rainbow Range volcanics of west-central British Columbia (Bevier, 1978).

In order to assess the relative importance of fractional crystallization versus partial fusion processes on the basis of major elements, a representative suite of both liquid and residual crystal phases is necessary. Presnall (1969) indicates that fractional fusion will produce a discontinuous liquid series and a continuous residual crystal series, while fractional crystallization will produce a continuous liquid series and a discontinuous residual crystal series. At Heart Peaks there appears to be a continuous series of liquid compositions as seen in oxide variation diagrams. If coarse grained inclusions found in Heart Peaks and Level Mountain Group lavas represent the residual crystals after fractional crystallization, then the compositions of these cognate inclusions may be as important as the liquid compositions, as reflected in the analyses of flows, in determining how the residual crystal series varies.

Trace elements may be the most useful evidence in formulating models for the derivation of basaltic liquids (Baker, 1977; Ferrara and Treuil, 1974; Gast, 1968). Gast (1968) has shown that high abundances

of the large cations, Rb, Sr, Ba and Zr which are typical of alkaline magmas would be produced by small degrees (3-7%) of partial melting of peridotitic mantle. Alkali basalt of the Level Mountain Group contain high abundances of the large-ion lithophile elements compared to the relatively depleted values typical of tholeiitic rocks.

Continuous major and trace element variations in rocks of the Level Mountain Group support a fractional crystallization model. The most abundant mafic magma composition, alkali basalt, is a likely parent for hawaiite, trachybasalt, and minor andesite which are derived by fractional crystallization. Mafic ankaramite may be the result of accumulation of pyroxene and olivine crystals which are important early crystallizing phases. Early crystallization of these phases would cause initial enrichment in residual liquids of Rb, Ba, Sr and Zr as seen in Figure 15. Major elements reflect this in the depletion of Ca, Mg and Ti in residual liquids. The scatter of points in the MgO and FeO versus SiO_2 diagrams may indicate settling and mixing of olivine phenocrysts in hawaiite and trachybasalt. After pyroxene and olivine, crystallization of plagioclase caused a depletion of Sr in hawaiite and trachybasalt, reversing its initial enrichment in the residual liquids. Ba was rapidly depleted with the onset of alkali feldspar crystallization. Rb, K and Na continue to be enriched in residual liquids. Apparent disequilibrium feldspar assemblages may indicate that mixing of early formed crystals with more or less evolved liquids has occurred.

Gabbroic and dioritic inclusions contain titanopyroxene, olivine,

kaersutite, plagioclase and alkali feldspar, all phases which are principal constituents of Level Mountain Group eruptive rocks. Rare aluminous spinel inclusions may represent a cognate phase which crystallized in a high temperature regime from basaltic magma.

Intermediate and Silicic Magmas

The occurrence of alkaline and subalkaline silicic lavas in the same volcanic province is a problem discussed by Ewart et al., (1976) for the association of metaluminous and peralkaline rhyolites in eastern Australia, and by Kiselev et al., (1978) for contemporaneous alkaline and tholeiitic rocks in the Baikal Rift. Differing magma types have been suggested to be related by high pressure fractional crystallization, (Kiselev et al., 1978) fractional crystallization modified by crustal contamination, or melting of different source rocks (Ewart et al., 1976).

Intermediate rocks of the Level Mountain Group and silicic rocks of the Heart Peaks Formation have transitional to subalkaline compositions compared to consistently alkaline mafic compositions in the Level Mountain Group. Representative analyses of silicic rocks are lacking mainly due to difficulties in sampling these highly altered rocks. Silica values have been affected most in the altered rocks where they are unrealistically high. This lack of representative compositions makes the link between the rocks of the Level Mountain Group and the Heart Peaks Formation obscure. Theories for the generation of contemporaneous rhyolitic and basaltic magmas which involve melting of different source rocks and the tapping of magma reservoirs containing

contrasting magma types all presuppose the existence of magmas of contrasting compositions. However, fractional crystallization and fractional melting are mechanisms which will extend the liquid line of descent. Factors such as high pressure fractionation, H_2O content, oxygen activity and temperature conditions in intermediate magmas may give considerable scope in the development of residual silicic liquids.

Oxygen isotope data indicates that crustal contamination cannot be a significant factor affecting mafic or silicic magmas at Heart Peaks. In the light of information from Edziza and the Rainbow Range in British Columbia, a fractional crystallization mechanism seems to be applicable to the Heart Peaks volcanics. Investigation of high pressure megacrysts and cumulates in the Heart Peaks volcanics may provide evidence regarding the applicability of high pressure fractionation as a factor responsible for the existence of both alkaline and subalkaline compositions.

Oxygen and Strontium Isotopes

δO^{18} values for basalt in the order of 5‰ are indicative of uncontaminated mantle derived basaltic material (Taylor, 1968). High O^{18} values for rhyolite may indicate high water contents during the crystallization of intermediate and silicic magmas when equilibration could occur between the magma and O^{18} rich water.

The $^{87}Sr/^{86}Sr$ ratio of 0.70344 for alkali basalt is another indicator that basalt was derived from a mantle source and is unaffected

by crustal contamination, however, the high isotopic ratio in rhyolite requires that some consideration be given to alteration and contamination mechanisms.

CHAPTER IX

CONCLUSIONS

The geology of the late Cenozoic volcanics of the Heart Peaks plateau is dominated by two compositionally distinct rock units. Basaltic to intermediate rocks of the Level Mountain Group, which are texturally and compositionally similar to the basaltic rocks in the Level Mountain Range to the east, have built a flat-lying succession unconformably above deformed and metamorphosed, pre-Cenozoic sedimentary and volcanic rocks. The Heart Peaks Formation is composed of silicic flows and pyroclastic rocks erupted in the same time interval as rocks of the Level Mountain Group. The association of alkali basalt and rhyolitic eruptives can be seen in other late-Cenozoic eruptive centres of northern British Columbia such as the Level Mountain centre east of Heart Peaks and the Edziza Range to the south. Silicic rocks at Heart Peaks, however, do not show the strongly enriched alkaline chemistry and mineralogy typical of the Edziza and Level Mountain centres. The mineralogy and chemistry of the silicic rocks of the Heart Peaks Formation is distinctly non-peralkaline.

Volcanic rocks of the Heart Peaks area show characteristics of the alkali olivine basalt series common to numerous centres around the world. The common association of alkaline volcanism with continental tensional tectonic environments has been emphasized, particularly with respect to Cenozoic volcanism. Comparisons of magma associations

and geophysical characteristics of well known volcanic centres with Heart Peaks and northern British Columbia in general reveals numerous similarities which may support the model of a tensional tectonic regime in northern British Columbia.

Though volcanism at Heart Peaks is closely related in space and time with rocks of the Level Mountain and Mount Edziza Ranges of northern British Columbia, the occurrence of non-peralkaline intermediate and silicic rocks in the Heart Peaks Formation is an important exception to the compositional trends of late Cenozoic volcanics in the Stikine belt of northern British Columbia.

Petrography of lavas shows textures typical of fluid, fissure type eruptives of basaltic and intermediate magma. High viscosity of silicic eruptives is reflected by their occurrence as steep sided domes composed of glassy and porphyritic flows and fine grained pyroclastics. Similarities in mineralogy among the eruptive series and the coarse-grained inclusions and megacrysts illustrates a genetic link for these suites.

Mineralogical variations in the Level Mountain Group can be seen in the continuous variation of plagioclase feldspars from An_{68} to An_{43}. Olivine shows a wide compositional variation from $Fo_{85}Fa_{15}$ to $Fo_{55}Fa_{45}$. Ca-rich pyroxene compositions show a restricted compositional range typical of the alkali olivine basalt series in general. kaersutite megacrysts are similar in composition to amphibole found as a major groundmass phase in andesite. In the Heart Peaks Formation,

rhyolite contains sanidine with a narrow compositional range and trachyte contains orthoclase showing exsolution of an albite-rich phase in an orthoclase-rich host. Apparent disequilibrium feldspar assemblages and complex zoning in feldspars indicates some degree of mixing of early formed crystals with more or less evolved liquids and fluctuation of H_2O activity.

Major and trace element variations are suggested to be due to a fractional crystallization process. The effect of partial melting mechanisms are difficult to distinguish from fractional crystallization effects when eruptive products only are being considered, but the closely modelled behaviour and mass balance calculations applied to alkali basalt series for fractional crystallization processes is much better known.

While a mantle derivation for alkali basalt magma is suggested by oxygen and strontium isotope values, speculation on the origin of rhyolite from the Heart Peaks Formation requires more extensive investigation with respect to isotope data.

Mineralogical and chemical differences between silicic rocks at Heart Peaks and those at other centres in the Stikine Belt may indicate systematic differences in source regions, fractionation conditions or crustal environment within this volcanic region. This possibility should be considered in any further study of the volcanic regime of northern British Columbia.

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APPENDIX A

WHOLE ROCK ELECTRON MICROPROBE ANALYSES

	1	2	3	4	5	6	7	8	9
SiO_2	44.55	45.95	45.93	46.20	47.89	47.10	47.67	47.80	47.41
TiO_2	3.54	3.48	4.10	3.10	2.93	3.07	3.13	1.10	3.37
Al_2O_3	14.88	15.43	15.69	15.34	16.23	16.72	16.45	21.25	17.26
Fe_2O_3	2.59	3.48	3.18	2.90	2.47	2.73	2.90	2.74	2.75
FeO	8.13	11.12	9.97	9.09	7.75	8.56	9.10	8.59	8.60
MnO	0.12	0.19	0.17	0.16	0.11	0.16	0.16	0.11	0.12
MgO	9.24	5.76	5.53	8.25	6.99	6.97	5.52	6.18	5.16
CaO	10.60	9.52	9.25	9.43	8.91	8.97	10.09	8.63	9.02
Na_2O	3.33	3.28	3.79	3.20	4.01	3.41	2.92	3.10	3.48
K_2O	1.88	0.85	1.05	1.12	0.94	1.75	1.14	0.28	1.15
P_2O_5	1.09	0.63	1.03	0.84	0.80	0.74	0.74	0.11	1.36
Total	99.95	99.70	99.60	99.71	99.03	99.60	99.83	99.91	99.68
Q	-	-	-	-	-	-	-	-	-
or	11.13	4.87	6.21	6.65	5.61	10.35	6.75	1.66	6.80
ab	11.96	21.21	28.62	25.00	31.78	24.74	24.71	26.26	30.30
an	20.11	23.70	23.52	24.27	23.74	25.94	28.56	42.15	27.64
ne	8.79	3.07	1.87	1.18	1.35	2.23	-	-	-
di	20.30	14,68	12.75	13.87	12.58	11.13	14.00	-	6.69
hy	-	-	-	-	-	-	8.01	11.67	7.00
ol	14.69	19.62	12.22	16.94	13.82	14.08	6.06	11.71	8.01
mt	3.76	5.03	4.61	4.22	3.62	3.96	4.21	3.77	3.99
il	6.73	6.40	7.79	5.91	5.61	5.83	5.95	2.09	6.40
ap	-	1.42	2.39	1.96	1.86	1.72	1.72	0.26	3.16

	10	11	12	13	14	15	16	17	18	19	20
SiO_2	47.34	47.83	47.55	48.29	48.62	48.54	48.98	49.44	48.50	48.95	49.09
TiO_2	3.08	2.12	2.98	3.09	2.94	2.64	2.88	2.42	2.43	2.85	2.29
Al_2O_3	15.66	15.38	16.26	16.55	15.77	16.72	16.50	16.46	17.57	16.35	17.72
Fe_2O_3	3.24	2.90	2.66	2.70	2.99	2.57	2.55	2.42	2.34	2.58	3.12
FeO	10.15	9.20	8.30	8.25	9.39	8.04	8.00	7.60	7.28	8.07	9.73
MnO	0.17	0.12	0.19	0.14	0.14	0.11	0.17	0.14	0.14	0.15	0.12
MgO	4.82	9.24	7.84	6.21	5.21	6.07	5.87	6.05	5.01	7.77	5.71
CaO	9.62	9.00	9.50	8.31	8.54	9.03	8.82	7.92	8.76	9.65	8.34
Na_2O	3.66	3.02	3.58	3.71	4.10	3.72	3.36	4.13	4.62	2.75	3.30
K_2O	1.17	0.98	1.92	1.93	0.96	1.65	1.82	2.41	2.56	1.74	1.45
P_2O_5	0.68	0.39	-	1.22	0.73	0.81	0.85	0.75	-	-	-
Total	99.60	100.21	100.78	100.40	99.39	99.90	99.80	99.73	99.21	100.85	100.87
Q	-	-	-	-	-	-	-	-	-	-	-
or	6.93	5.86	11.29	11.42	5.68	9.77	10.79	14.29	15.26	10.20	8.50
ab	27.93	25.24	17.03	30.84	34.69	28.74	28.49	27.61	17.71	23.07	27.68
an	22.44	25.51	22.49	22.53	22.34	24.07	24.59	19.31	19.80	26.90	29.00
ne	2.13	0.31	7.08	0.30	-	1.50	-	4.03	11.75	-	-
di	17.65	13.77	19.62	8.68	13.91	12.55	11.12	13.26	19.55	16.57	9.87
hy	-	-	-	-	1.00	-	4.43	-	-	0.63	3.15
ol	10.77	20.07	13.01	13.76	11.74	12.71	9.41	12.61	7.84	13.53	12.97
mt	4.71	4.25	3.83	3.77	4.34	3.73	3.71	3.52	3.42	3.71	4.49
il	5.86	4.07	5.63	5.87	5.58	5.02	5.48	4.61	4.65	5.37	4.31
ap	1.58	0.91	-	2.83	1.69	1.88	1.98	1.74	-	-	-

	21	22	23	24	25	26	27	28	29	30
SiO_2	50.64	52.50	52.06	54.78	59.00	62.94	64.35	71.75	71.83	71.75
TiO_2	1.62	2.53	1.93	1.36	1.45	0.84	0.83	0.17	0.29	0.16
Al_2O_3	16.62	16.85	18.20	16.75	16.26	16.24	16.80	15.33	17.11	16.10
Fe_2O_3	2.45	2.17	2.13	1.84	1.60	1.38	1.03	0.30	0.12	0.15
FeO	7.66	6.78	6.66	5.78	5.02	4.32	3.23	0.61	0.70	0.46
MnO	0.15	0.27	0.14	0.09	0.06	0.13	0.27	-	-	-
MgO	5.19	3.47	5.41	3.86	2.93	0.80	0.26	-	-	-
CaO	7.69	8.71	9.23	8.21	5.55	2.32	1.66	0.05	-	0.40
Na_2O	4.20	4.18	3.96	4.16	4.60	5.47	5.76	4.49	3.81	5.02
K_2O	1.81	3.19	1.34	2.55	2.73	4.79	4.89	7.01	7.14	5.65
P_2O_5	0.84	-	-	0.55	0.58	0.29	0.40	0.17	-	-
Total	98.97	100.65	101.06	99.93	99.78	99.52	99.48	99.88	101.10	99.67
Q	-	-	-	-	6.52	5.73	7.44	18.88	21.77	19.90
or	10.73	18.75	7.84	15.09	16.21	28.52	29.08	41.47	41.83	33.52
ab	35.60	26.18	33.15	35.22	38.92	46.49	48.99	37.99	31.92	42.61
an	21.18	17.67	27.63	19.51	15.62	5.60	5.56	-	-	1.89
ne	-	4.85	-	-	-	-	-	-	-	-
di	9.17	20.74	14.35	14.45	6.65	3.41	0.07	-	-	-
hy	6.00	-	1.06	8.14	9.64	5.92	4.84	0.59	0.70	0.46
ol	4.57	3.89	9.26	1.03	-	-	-	-	-	-
mt	5.89	3.13	3.06	2.67	2.32	2.01	1.50	0.44	0.17	0.22
il	4.87	4.77	3.63	2.59	2.75	1.60	1.59	0.32	0.55	0.31
ap	1.96	-	-	1.28	1.35	0.70	0.93	0.35	-	-

1.	0788-12	Alkali Basalt, LMG
2.	4261-19	Alkali Basalt, LMG
3.	4262-17	Hawaiite, LMG
4.	4261-6	Alkali Basalt, LMG
5.	0788-19	Hawaiite, LMG
6.	4261-33	Alkali Basalt, LMG
7.	4261-16	Tholeiitic Basalt, LMG
8.	0788-14	Basalt, LMG
9.	0788-6	Basalt, LMG
10.	7/3-1K	Hawaiite, LMG
11.	4261-22	Alkali Basalt, LMG
12.	7786-17	Alkal Basalt, LMG
13.	7786-1	Alkali Basalt,LMG
14.	0788-9	Hawaiite ,LMG
15.	0788-8	Hawaiite, LMG
16.	4260-1	Tholeiitic Basalt ,LMG
17	7786-11	Trachybasalt, LMG
18.	7786-21	Trachybasalt, LMG
19.	7786-19	Tholeiitic Basalt ,LMG
20.	4261-34	Basalt, LMG
21.	4261-40	Hawaiite, LMG
22.	7786-22	Trachybasalt, LMG
23.	1015-6	Hawaiite, LMG
24.	0788-17A	Trachybasalt, LMG
25.	7788-13A	Andesite, LMG
26.	0789-5	Dacite, HPF
27.	SP5	Rhyolite, HPF
28.	7789-6	Rhyolite, HPF
29 .	0789-3	Rhyolite, HPF
30.	0789-11	Rhyolite, HPF

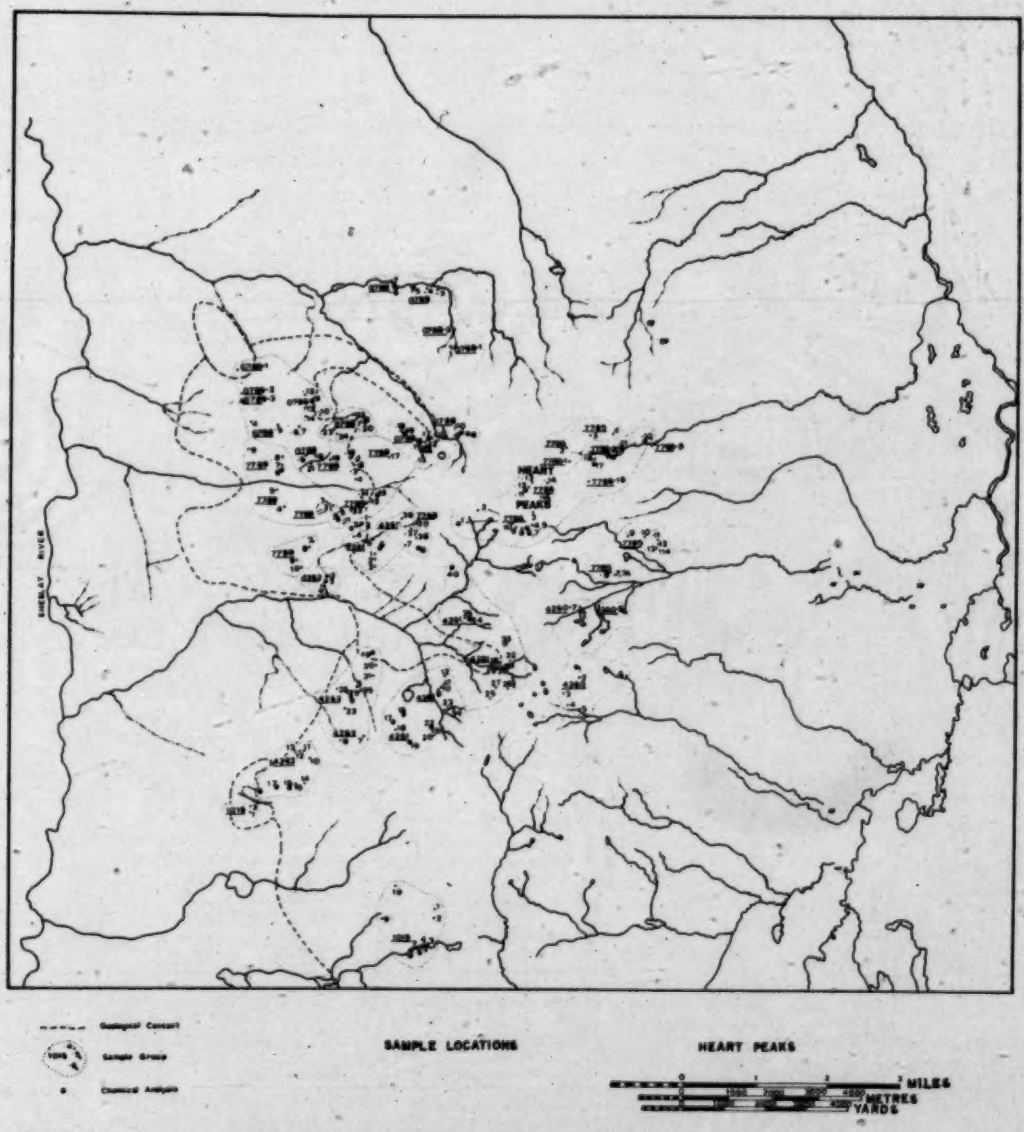

Fig. 19. Heart Peaks area sample locations.

APPENDIX B

MICROPROBE MINERAL ANALYSES

Feldspar

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	51.24	57.73	58.15	52.18	66.36	53.10	53.50	53.71	68.41	66.32	53.26
TiO_2	0.15	0.08	0.14	0.11	0.17	-	0.10	0.18	-	0.05	0.31
Al_2O_3	27.97	26.71	24.74	29.62	19.96	30.32	30.03	29.68	18.74	19.70	29.12
FeO	2.23	0.41	1.16	0.51	0.65	0.44	0.51	1.16	0.16	0.23	0.45
MgO	0.23	-	-	-	-	-	-	0.27	-	-	-
CaO	13.36	8.79	7.58	12.28	1.61	12.53	12.31	12.12	0.77	0.70	11.80
Na_2O	4.04	5.96	6.38	3.89	5.72	4.23	4.46	4.52	6.33	6.67	4.16
K_2O	0.35	0.58	1.11	0.36	4.70	0.25	0.27	0.30	6.57	7.06	0.53
Total	99.51	100.26	99.26	98.95	99.17	100.89	101.18	101.94	100.97	100.73	100.43
	No. of Ions on the basis of 8 oxygens										
Si	2.26	2.60	2.64	2.40	2.96	2.39	2.40	2.40	3.02	2.95	2.40
Al	1.45	1.44	1.32	1.60	1.05	1.61	1.59	1.56	0.98	1.03	1.59
Fe	0.08	0.02	0.04	0.007	0.02	0.02	0.021	0.04	0.006	0.008	0.02
Ti	0.005	-	0.005	0.004	0.006	-	0.003	0.006	-	-	0.01
Mg	0.01	-	-	-	-	-	-	0.01	-	-	-
Na	0.35	0.52	0.56	0.35	0.50	0.37	0.39	0.39	0.54	0.58	0.36
Ca	0.63	0.42	0.37	0.60	0.08	0.61	0.59	0.58	0.04	0.03	0.57
K	0.02	0.03	0.06	0.02	0.27	0.01	0.02	0.02	0.37	0.40	0.03
Mol.% Or	2	3	6	2	32.5	1	1	2	39	40	3
Ab	35	52	37	36	58.5	37.5	39	39.5	57	57	38
An	63	43	57	62	9	61.5	60	58.5	4	3	59

(continued)

Pyroxene

	1	2	3	4	5
SiO_2	50.31	46.16	46.60	47.27	49.66
TiO_2	2.46	2.57	1.80	3.35	1.28
Al_2O_3	2.46	8.80	9.90	5.32	6.85
FeO	13.09	6.97	8.49	11.26	7.99
MnO	0.23	-	0.15	0.14	-
MgO	10.89	13.00	10.84	12.20	12.54
CaO	20.83	20.92	21.05	21.22	20.74
Na_2O	0.73	0.89	1.36	0.66	1.78
K_2O	0.04	0.10	-	-	-
Total	101.04	99.4	100.19	101.42	100.84

No. of Ions on the basis of 6 oxygens

Si	1.90	1.72	1.75	1.77	1.84
Al	0.11	0.38	0.44	0.23	0.30
Ti	0.04	0.07	0.05	0.09	0.04
Fe	0.41	0.27	0.27	0.35	0.25
Mg	0.61	0.73	0.61	0.68	0.69
Mn	0.008	0.06	0.005	0.005	-
Ca	0.84	0.84	0.85	0.85	0.82
Na	0.05	0.06	0.12	0.05	0.12
K	-	0.005	-	-	-

Mol.%	Mg	33	41	34.5	36	39
	Fe	22	12	16.5	19	14
	Ca	45	47	49	45	47

Olivine

	1	2	3
SiO_2	40.18	40.12	35.37
Al_2O_3	0.29	0.08	0.02
CaO	0.28	0.32	0.39
MgO	45.38	45.74	26.25
FeO	13.76	15.11	37.85
MnO	0.16	-	0.52
Na_2O	-	-	0.05
Total	100.05	101.37	100.45

No. of Ions based on 4 oxygens

Si	1.00	0.99	0.99
Al	0.008	0.003	0.006
Ca	0.007	0.008	0.01
Mg	1.68	1.69	1.10
Fe	0.29	0.31	0.89
Mn	0.003	-	0.01
Na	-	-	-

Mol.%	Fo	85	85	55
	Fa	15	15	45

	Opaque Oxides		Kaersutite
	1	2	
SiO_2	-	0.18	47.22
Al_2O_3	1.54	55.69	16.22
TiO_2	28.57	0.78	3.02
FeO	65.39	27.83	11.03
MnO	0.62	0.21	0.15
MgO	-	14.10	7.89
CaO	0.09	-	9.43
Na_2O	-	0.30	3.53
K_2O	-	-	1.85
Total	98.18		100.34

	No. of Ions based on 4 oxygens		No. of Ions based on 24 oxygens			
Si	-	0.005	Si	6.93	Q	-
Al	0.10	1.81	Al	2.81	or	10.91
Ti	1.24	0.02	Ti	0.33	ab	17.05
Fe	3.15	0.64	Fe	1.35	ar	22.87
Mn	0.03	0.005	Mn	0.02	ne	6.89
Mg	-	0.58	Mg	1.72	di	19.16
Ca	0.006	-	Ca	1.48	hy	-
Na	-	0.02	Na	1.00	ol	13.58
K	-	-	K	0.35	mt	3.83
					il	5.72

Feldspar

1.	7/3-1K	Labradorite Groundmass
2.	7/3-1K	Andesine Phenocryst
3.	7788-13A	Andesine Groundmass
4.	7788-13A	Labradorite Microphenocryst
5.	7788-13A	Sanidine
6.	0788-7	Labradorite Phenocryst
7.	0788-7	Labradorite Phenocryst
8.	0788-7	Labradorite Groundmass
9.	TOC	Sanidine
10.	TOC	Sanidine
11.	4261-20	Labradorite
12.	7788-8	Sanidine
13.	7788-8	Labradorite
14.	7788-8	Sanidine
15.	0788-6	Labradorite
16.	0788-6	Labradorite
17.	0788-6	Labradorite Groundmass
18.	0788-17	Labradorite
19.	0788-17	Labradorite
20.	0789-1	Labradorite
21.	0789-1	Labradorite
22.	0789-1	Labradorite Groundmass

Pyroxene

1.	7/3-1K	Augite Groundmass
2.	4261-19	Augite
3.	4261-19	Augite
4.	0788-7	Augite
5.	4261-20	Augite

Olivine

1.	4261-19
2.	4261-20
3.	0789-1

Opaque Oxides

1.	7/3-1K	Titanomagnetite
2.	4261-19	Spinel

APPENDIX C

ANALYTICAL METHODS

Electron Microprobe Analyses

Whole rock and mineral analyses were run on a ARL-EMX microprobe fitted with an ORTEC Si (Li) detector. A fully quantitative energy dispersive method was used. Methods used for background shaping and scaling, overlap corrections and adjustments for instrumental drift have been described by Smith (1975, 1976) and Smith and Gold (1975). The operating conditions were:

- 15 KV accelerating potential;
- 30 nA probe current;
- 400 seconds counting time;
- a focussed or scanning beam, depending on the object being analysed (from 16 by 16 to 600 by 400 microns scanning area).

Standards used were mineral and glass standards available in the microprobe lab. Standard numbers and descriptions are found in Table VI. For mineral analyses, all elements except Fe, Ti, and P were analysed against two standards as shown and results were averaged when the composition of the analysed specimen was not similar to the composition of the standard.

Rocks were prepared for microprobe analysis by grinding to a fine powder and then fusing them to a homogenous glass. Fusion of rock powders using an image furnace, as described by Schimann (1978), is advantageous in that it eliminates the problem of contamination from the sample container and loss of alkalis during the fusion process.

Energy dispersive analyses were processed by the computer program EDATA.

TABLE VI

ELECTRON MICROPROBE STANDARDS

Mineral Analyses:

ELEMENT	STANDARD	STANDARD NUMBER
Si	Sanidine	CLAM-7
	Obsidian	EPS11-6
Al	Albite	EPS11-1
	Sanidine	CLAM-7
Ti	Ilmenite	CLAM-5
Fe	Ilmenite	CLAM-5
Mg	Olivine	EPS12-6
	Diopside	CLAM-9
Ca	Bytownite	EPS11-2
	Diopside	CLAM-9
Na	Albite	EPS11-1
	Obsidian	EPS11-6
K	Sanidine	CLAM-7
	Obsidian	EPS11-6
P	Obsidian	EPS11-6

(cont'd.)

ELECTRON MICROPROBE STANDARDS

Whole Rock Analyses:

ELEMENT	STANDARD	STANDARD NUMBER
Si	Obsidian	639-10
Ti	Kakanui Pyrope	639-2
Al	Wicks Grossular	639-1
Fe	Kakanui Pyrope	639-2
Mn	Wicks Grossular	639-1
Mg	Kakanui Pyrope	639-2
Ca	Wicks Grossular	639-1
Na	Obsidian	639-10
K	Obsidian	639-10
P	Obsidian	639-10

XRF Analyses

X-ray fluorescence analyses were performed on pressed powder bricquetts using a polyvinyl alcohol binder, and both major and trace elements were determined on these briquetts by G. Holland (Holland and Brindle, 1966). A Philips 1212 automatic X-ray fluorescence spectrometer was used, coupled to a Torrens TE 108 automatic sample holder and interfaced to a card punch for direct data handling by computer.

Oxygen Isotope Analyses

Samples for oxygen isotope analysis were collected using the Bromine Pentafluoride method similar to that described by Clayton and Mayeda (1963). Analyses are reported in units where:

$$O^{18} = \frac{{}^{18}O/{}^{16}O_{(sample)} - {}^{18}O/{}^{16}O_{(standard)}}{{}^{18}O/{}^{16}O_{(standard)}} \; 10^3 \; ‰$$

The oxygen isotopic ratio of standard mean ocean water (SMOW) is used as a standard for reporting oxygen isotope variations.

Penfield H_2O Analyses

Total water contents (H_2O^+ and H_2O^-) were determined by fusion of a known quantity of rock powder (1g.) with PbO as a flux (.5g.). Water driven off was condensed and weighed in Penfield tubes. From total water, atmospheric water (H_2O^-) was subtracted. Correction was also made for water contained in the PbO flux.